A STRATEGY FOR DELINEATING THE AREA OF GROUND-WATER CONTRIBUTION TO WELLS COMPLETED IN FRACTURED BEDROCK AQUIFERS IN PENNSYLVANIA

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
	Length	
inch	25.4	millimeter
foot	0.3048	meter
mile	1.609	kilometer
	Area	
square feet	0.0929	square meter
square mile	2.590	square kilometer
	Volume	
gallon	3.785	liter
cubic foot	0.02832	cubic meter
	Flow	
cubic foot per second	0.02832	cubic meter per second
gallons per minute	0.06309	liters per second
million gallons per day	43.81	liters per second
	Other Conversions	
foot per day	0.3048	meter per day
foot squared per day	0.0929	meter squared per day

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ABSTRACT

Delineating a contributing area to a well completed in a fractured bedrock aquifer in Pennsylvania is difficult because the hydrogeologic characteristics of fractured rocks are extremely complex. Because of this complexity, a single method or technique to delineate a contributing area will not be applicable for all wells completed in fractured-bedrock aquifers. Therefore, a strategy for refining the understanding of boundary conditions and major heterogeneities that control ground-water flow and sources of water to a supply well is suggested.

The strategy is based on developing and refining a conceptual model for the sources of water to the well. Specifically, the strategy begins with an initial conceptual model of the ground-water-flow system, then requires the collection of hydrogeologic information to refine the conceptual model in a stepwise manner from one or more of six categories: (1) hydrogeologic mapping, (2) water-level and streamflow measurements, (3) geochemistry, (4) geophysics and borehole flowmetering, (5) aquifer testing, and (6) tracer testing.

During the refinement process, the applicability of treating the fractured-rock aquifer as a hydrologic continuum is evaluated, and the contributing area is delineated. Choice of the method used to delineate the contributing area is less important than insuring that the method is consistent with the refined conceptual model. By use of such a strategy, the improved understanding of the ground-water-flow system will lead to a technically defensible delineation of the contributing area.

INTRODUCTION

More than 2 million people in Pennsylvania depend on ground water for their supply of potable water (Solley and others, 1983, p. 10). Unfortunately, contamination of ground water withdrawn by community-supply wells and springs is a problem in some urban and agricultural areas (Barker, 1988). When ground water is contaminated, difficult and costly treatment methods or alternative sources commonly are required to insure a safe drinking-water supply. Ground-water contamination near public-supply wells and springs can be minimized or eliminated entirely by protecting the area surrounding these wells and springs from activities that can adversely affect ground-water quality. This strategy is termed wellhead protection.

The 1986 Amendments to the Safe Drinking Water Act (section 1428) established the Wellhead Protection Program to protect ground water used for public drinking supplies from possible contamination. Each state is required by the Amendments to develop a wellhead-protection program that includes the delineation of wellhead-protection zones. These zones are defined in the Safe Drinking Water Act Amendments as "the surface and subsurface area surrounding a water well or well field, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or well field" (U.S. Environmental Protection Agency, 1987, p. 1-2). This definition is similar to that used by hydrologists for the contributing area to a well or spring.

The size and shape of the contributing area to a well or spring can be estimated by a variety of methods that are formulated on principles of flow in a relatively homogeneous hydrologic continuum. These methods usually are applied successfully in unconsolidated sand and gravel aquifers (U.S. Environmental Protection Agency, 1987; Morrissey, 1987; Risser and Madden, 1994). Unfortunately, ground-water flow in bedrock aquifers in Pennsylvania usually is through a complex network of fractures and solution-enlarged openings that may not be easily characterized or simulated at the well-field scale. Thus, a strategy is needed for evaluating fractured-rock aquifers and delineating contributing areas to wells in Pennsylvania. The Pennsylvania Department of Environmental Resources (PaDER), Bureau of

Water Supply and Community Health, is developing a wellhead-protection program for the Commonwealth. In cooperation with PaDER, the U.S. Geological Survey is evaluating approaches that can be used to delineate the contributing area for wells completed in bedrock aquifers throughout Pennsylvania.

Purpose and Scope

This report describes a strategy to delineate contributing areas to wells completed in bedrock aquifers that can be used by PaDER to assist communities in establishing local wellhead-protection plans for bedrock aquifers. The strategy is based on developing and refining a conceptual model for sources of water contributed to a pumping well. Thus, this report outlines hydrologic investigations in six categories that are useful for refining the understanding of ground-water flow to a well in a fractured-bedrock aquifer. Application of the strategy is illustrated by the use of a hypothetical aquifer setting.

Previous Investigations

Several publications evaluate and summarize techniques being used to delineate wellhead-protection areas in fractured rocks. The U.S. Environmental Protection Agency (1987) guidelines include an evaluation of assumptions, data requirements, and technical merits of methods that can be used to estimate contributing areas for wells in various hydrogeologic settings. Although the U.S. Environmental Protection Agency report focuses on methods applicable to porous media, the complexities of wellhead protection in fractured rocks are discussed. Skinner (1985) discusses the difficulties of wellhead protection in fractured-bedrock aquifers and emphasizes the importance of understanding the ground-water-flow system—especially fracture-matrix interrelations, connections with surface-water systems, and conditions in the unsaturated zone. The U.S. Environmental Protection Agency (1991) outlines three methods for delineating contributing areas in fractured-rock aquifers. They describe and apply flow-system mapping, residence-time calculations, and numerical modeling at two well fields in Wisconsin.

Contributing Area and Related Terms

The terms "area of diversion," "contributing area," and "time-of-travel area" are used in this report. Several authors have used other terms to define a similar area or volume around a well. Because of the subtle differences in these terms and their inconsistent usage in wellhead-protection studies, a brief discussion of the terms as used in this report follows, and a glossary is provided at the end of the report.

The zone of diversion is the aquifer volume through which water is diverted to the well (fig. 1). This volume also has been termed "capture zone" (Keely and Tsang, 1983). The projection of this volume to land surface defines the well's area of diversion (Brown, 1963) and is equivalent to the "Zone II" wellhead protection area defined by PaDER (Commonwealth of Pennyslvania, 1994). The contributing area is the area of diversion and any areas that provide recharge to the aquifer within the zone of diversion (Morrissey, 1987, p. 10). This area is equivalent to the sum of PaDER's "Zone II" and "Zone III" wellhead protection areas. Because it includes additional areas, the contributing area can be much larger than the well's area of diversion. The differences in these terms is important because most methods to delineate the contributing area of a well actually provide only a delineation of its area of diversion. Contributing areas that are not part of the area of diversion usually must be delineated indirectly.

The difference between the area of diversion and the contributing area is best illustrated in valley settings underlain by carbonate rocks (fig. 1). The area of diversion in this example includes only that part of the carbonate-rock aquifer through which water is diverted to the well. This area would also be the contributing area if precipitation on the carbonate-rock aquifer surface were the only source of recharge. However, because a stream that flows from the adjacent crystalline-bedrock uplands loses water to the aquifer as it crosses the area of diversion to the well, the contributing area of the well includes the watershed of that stream on the upland surface (fig. 1). Similarly, if river water is induced to flow to the well (not shown in figure 1), the entire watershed of the river upstream from the well would need to be included in the contributing area. Therefore, an understanding *of all sources of water* that enter the well's area of diversion is needed for proper delineation of its contributing area.

The part of the area of diversion from which water will reach a well within a specified time is a time-of-travel area. For example, a 1-year time-of-travel area is shown in figure 1. Time-of-travel areas are

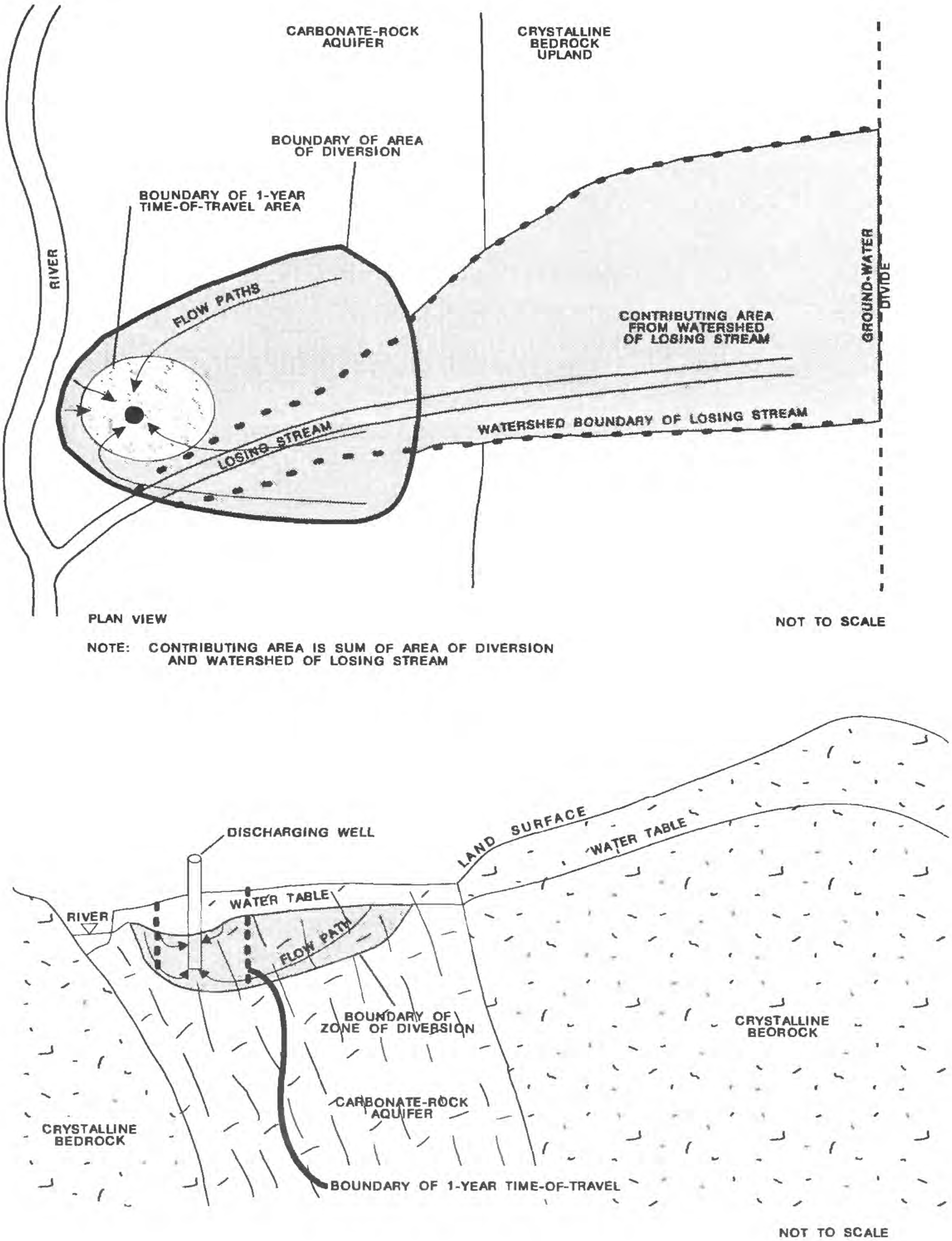

Figure 1. Area of diversion, contributing area, and time-of-travel area around a discharging well.

usually delineated on the basis of the average advective velocity of ground water. However, processes of hydrodynamic dispersion, chemical diffusion, and retardation can cause contaminants to reach the well before or after the arrival time estimated from the average advective velocity of ground water.

Characteristics of Bedrock Aquifers in Pennsylvania

Because Pennsylvania is not covered by extensive deposits of stratified unconsolidated sediments, bedrock aquifers provide the major source of water to public-supply wells. About three-fourths of the ground water withdrawn in the Commonwealth is from bedrock aquifers (U.S. Geological Survey, 1990, p. 435).

The U.S. Geological Survey's Ground Water Site Inventory (GWSI) data base for Pennsylvania contains records of 2,953 wells drilled in bedrock aquifers for public supply and fewer than 300 wells drilled in unconsolidated sediments for public supply. The data base lists 746 wells in the Appalachian Plateau Physiographic Province, 988 wells in the Ridge and Valley Physiographic Province, and 1,219 wells in the Piedmont, Blue Ridge, and New England Physiographic Provinces (table 1).

Bedrock aquifers in Pennsylvania can be divided into three major categories—siliciclastic, carbonate, and crystalline. Because these rocks have undergone great stress from tectonic forces or deep burial, their primary porosity has been mostly destroyed. Thus, the occurrence and movement of ground water is chiefly within fractures and solution-enlarged openings. The generalized distribution of bedrock aquifers is shown in figure 2.

The siliciclastic rocks consist mainly of sandstone, siltstone, shale, and conglomerate. They range in age from Cambrian to Triassic and are widely distributed throughout Pennsylvania (fig. 2). The siliciclastic rocks are heavily relied on for water supply in the Appalachian Plateau Physiographic Province, where nearly all wells completed in bedrock aquifers obtain water from flat-lying Paleozoic siliciclastic rocks (table 1). In the Ridge and Valley and the Piedmont Physiographic Provinces of Pennsylvania, more public-supply wells are completed in siliciclastic rocks than in the carbonate and crystalline rocks combined. The depths of public-supply wells in siliciclastic rocks typically range from 100 to 530 feet (10th to 90th percentiles of all depths). Yields of wells in siliciclastic rocks are variable, ranging from about 10 to 300 gallons per minute (10th to 90th percentiles of all yields), and are greatest from wells in siliciclastic rocks of the Piedmont Physiographic Province (table 1).

Table 1. *Summary of ground-water withdrawals, depth, yield, and specific capacity for wells drilled in bedrock aquifers for public supply in Pennsylvania*

[Estimated withdrawal data are from the Pennsylvania Water-Use Data Base; other data are from the U.S. Geological Survey's Ground-Water Site Inventory for wells where the water-producing geologic unit was recorded; specific-capacity data are for various pumping durations; gal/min, gallon per minute; Mgal/day, million gallons per day; Q_{10}, 10 percent of all values are less than this amount; Q_{90}, 90 percent of all values are less than this amount; --, no data]

Physiographic province and dominant lithology	Estimated ground-water withdrawals during 1990 (Mgal/d)	Total number of wells with record of depth	Depth (feet)			Total number of wells with record of yield	Yield (gal/min)			Total number of wells with record of specific capacity	Specific capacity (gallons per minute per foot)		
			Q_{10}	Q_{90}	Median		Q_{10}	Q_{90}	Median		Q_{10}	Q_{90}	Median
Appalachian Plateaus	28.5	746	77	500	210	649	10	200	40	329	0.20	10.7	1.1
Siliciclastic	28.5	735	77	500	212	644	10	200	40	328	.20	10.7	1.1
Carbonate	--	7	--	--	112	2	--	--	30	1	--	--	3.0
Crystalline	--	4	--	--	98	3	--	--	4	0	--	--	--
Ridge and Valley	55.2	988	128	530	300	885	12	420	65	539	.01	45	1.6
Siliciclastic	11.3	714	123	550	300	628	10	250	5	356	.01	9.3	1.0
Carbonate	43.9	272	143	500	289	255	18	1,000	140	181	.52	164	12.5
Crystalline	--	2	--	--	440	2	--	--	60	2	--	--	1.4
Piedmont, Blue Ridge, and New England	32.9	1,219	115	517	308	1,130	20	390	100	658	.29	12	1.5
Siliciclastic	20.8	852	132	550	331	784	20	350	121	449	.30	8.4	1.5
Carbonate	4.7	156	85	507	298	151	13	950	200	90	.20	78	6.4
Crystalline	7.4	211	100	430	260	195	14	180	43	119	.20	5.6	.8

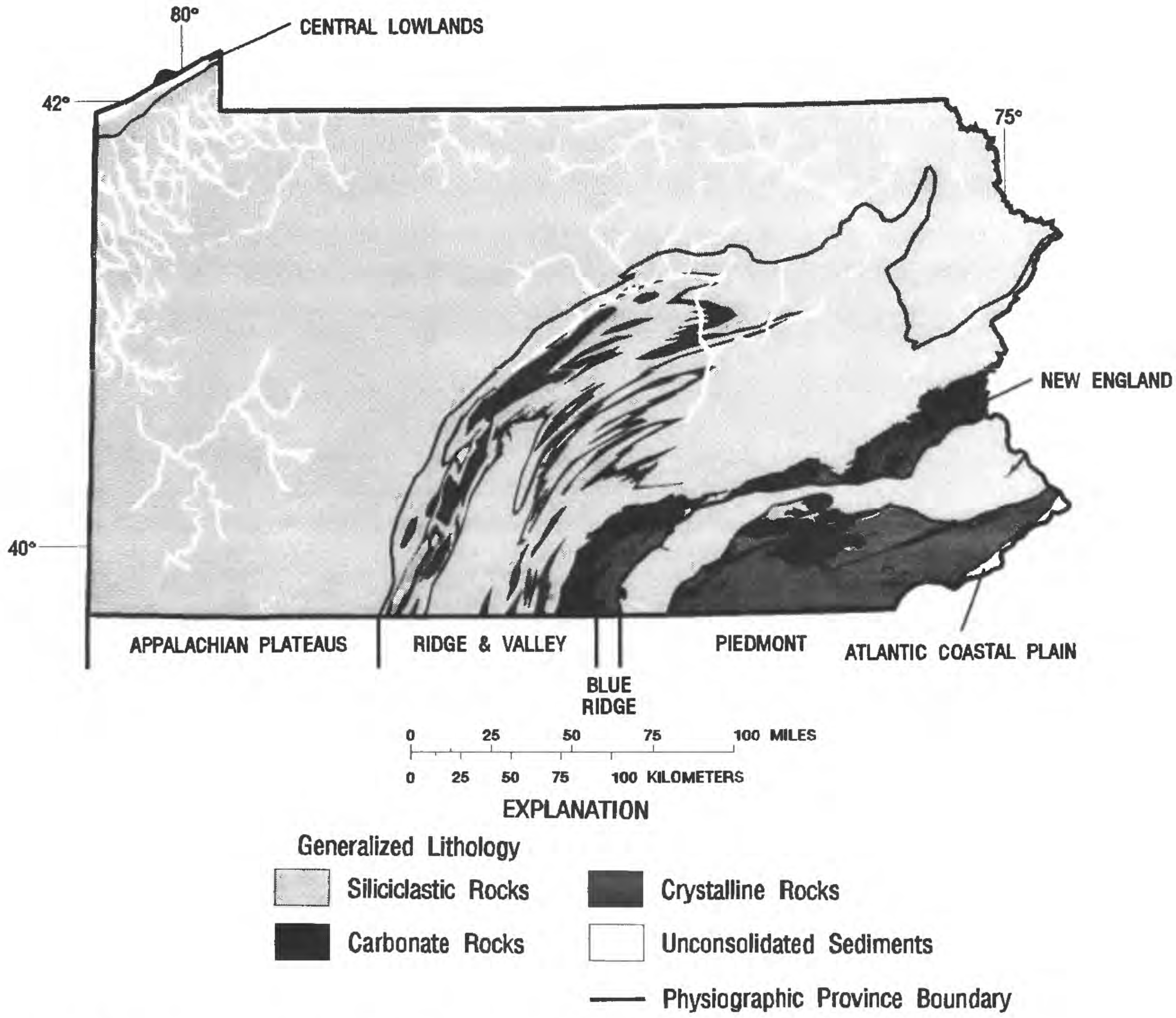

Figure 2. Physiography and generalized geology of Pennsylvania.

Carbonate rocks consist chiefly of limestone, dolomite, and marble of Cambrian through Devonian age. These rocks crop out mainly in the Ridge and Valley and the Piedmont Physiographic Provinces (fig. 2). Although public-supply withdrawals from carbonate rocks are insignificant in the Appalachian Plateau Physiographic Province, withdrawals in the Ridge and Valley and the Piedmont Physiographic Provinces total about 48.6 million gallons per day (table 1). The depths of most public-supply wells completed in carbonate rocks typically range from 100 to 500 feet (10th to 90th percentiles of all depths). The greatest yields (2,400 gallons per minute) of wells in Pennsylvania were reported for those completed in carbonate rocks. Large yields of water from wells are possible because conduits have been formed by dissolution of carbonate bedrock. More typical yields (10th to 90th percentiles of all yields) of public-supply wells in carbonate rocks of the Ridge and Valley Physiographic Province range from 18 to 1,000 gallons per minute.

Igneous and metamorphic crystalline rocks include granite, diorite, greenstone, schist, phyllite, diabase, and gneiss. These rocks are mostly Precambrian to early Paleozoic in age and crop out in the southeastern part of Pennsylvania (fig. 2). Withdrawals for public supply average about 7.4 million gallons per day from crystalline rocks in the Piedmont Physiographic Province (table 1). The depths of wells typically range from 100 to 430 feet (10th to 90th percentiles of all depths). Typical yields (10th to 90th percentiles of all yields) range from 14 to 180 gallons per minute and are somewhat lower than for wells completed in other rock types (table 1). The smaller yields probably are caused by fewer fractures in the crystalline rocks compared to those in siliciclastic and carbonate rocks.

EVALUATING GROUND-WATER FLOW IN BEDROCK AQUIFERS

Ground water moves through the porous matrix, fractures, and conduits within bedrock aquifers. The porous matrix is the void space between the solid particles or crystals that formed at the same time as the rock. Fractures are defined in many ways, but in this report they refer to any secondary openings in the rock, such as bedding partings, cracks, joints, cleavage, schistosity, and faults, that have not been filled by mineral deposits but may have been solutionally widened. Conduits are open channels and pipes that have been enlarged by dissolution and are found primarily in carbonate rocks.

Bedrock aquifers are classified in this report according to the dominant type of pathway (pores, fractures, or conduits) through which ground water flows (table 2). The type of pathway affects the hydrogeologic properties of the aquifer, such as the flow regime, homogeneity, isotropy, and water-table configuration—all of which influence the shape of the contributing area around a well. The hydrologic properties and rock types characteristic of ground-water flow through pores, fractures, and conduits are shown in table 2 and described below.

Flow in Porous Media

The flow of ground water through a porous medium usually is slow and laminar. At the scale of the pores, the velocity of ground-water flow varies widely because water in the center of a pore space moves faster than water near the pore wall and because the tortuous flow paths around individual grains cause deviations from the average flow direction. At the scale of a well field, ground-water flow can be accurately described as the average of the flow through the innumerable individual pores. A change in the scale of a sample of the porous medium (until pore-size scales are reached) does not affect the average flow rate of water per unit cross-sectional area of the sample. This "scale independence" allows a porous medium to be treated as a hydrologic continuum in which average values of aquifer properties can be used to adequately characterize the flow system. The hydraulic properties of a porous medium also tend to be more homogeneous and isotropic than those of fractured-bedrock aquifers (table 2).

Because a porous medium can be treated as a hydrologic continuum, the flow of ground water toward wells can be readily described mathematically (Lohman, 1972). Many analytical and numerical methods are available to delineate a contributing area for a well completed in a porous medium (U.S. Environmental Protection Agency, 1987).

Unfortunately, the dominant pathway of ground-water flow in bedrock aquifers in Pennsylvania is not usually through pore spaces. Although significant quantities of ground water can be present in the porous matrix of many siliciclastic and carbonate rocks (Davis and DeWiest, 1966, p. 349), fractures and conduits generally comprise the network through which water is transmitted to wells in Pennsylvania. In crystalline and dense carbonate rocks, the primary porosity of the rock matrix is extremely small. Nearly all ground water is stored in and moves through fractures or conduits.

Flow in Fractured Rock

The flow of ground water through fractures is extremely complex and is the subject of much current research (Barton and Hsieh, 1989; Dverstorp and others, 1992). Most research has been conducted to evaluate the hydrologic characteristics of potential repositories for hazardous wastes and, therefore, has largely focused on sites where ground water is present in small quantities and its flow is slow. Examples of such conditions include massive tuff, thick basalt, evaporites, thick shale, and sparsely fractured crystalline rocks. For the purpose of delineating the contributing area of a supply well, many of the approaches and techniques used to evaluate the hydraulic characteristics of low-permeability rocks are helpful. However, because a public-supply well yields a significant sustainable quantity of water, it must be connected to a reasonably extensive, integrated fracture system; otherwise, the well would quickly deplete water stored in the fractures and become dry. Therefore, most investigations of contributing areas of supply wells need to extend beyond the local-scale environment at which most current research in fractured rock is focused.

As shown in table 2, the characteristics of ground-water flow in fractures are extremely variable. Three basic approaches are available to quantitatively evaluate this complex flow: (1) discrete, (2) statistical, and (3) continuum (porous-media equivalency).

Table 2. *Relation of dominant pathway of ground-water flow in fractured bedrock aquifers to selected hydrogeologic properties*

[After White, 1988, table 6.1]

Hydrogeologic property	Dominant pathway of ground-water flow		
	Flow through porous matrix	Flow through fractures	Flow through conduits
Porosity type	Intergranular pores	Concentrations of joints and fractures Bedding plane partings (may be enlarged by solution)	Open channels and pipes of various sizes and shapes
Typical geologic material	Unconsolidated sediments, some siliciclastic rocks, and sandy dolomites	Most crystalline and siliciclastic rocks in Pennsylvania; many parts of carbonate-rock aquifers	Carbonate-rock aquifers
Homogeneity and isotropy with respect to hydraulic conductivity	More homogeneous and isotropic than for flow through fractures or conduits	Usually heterogeneous and anisotropic because of fracture spacing and preferred orientations May be statistically isotropic over large volumes	Usually highly heterogeneous and anisotropic
Flow regime	Laminar flow that can accurately be described as a hydrologic continuum	Usually laminar flow but may be turbulent near wells. Adequacy of continuum approximation depends upon density of interconnected fractures and the scale of the investigation	Turbulent flow in discrete pipes or channels that usually cannot accurately be described as a hydrologic continuum
Water-table configuration	Well-defined water-table surface	May be well defined or irregular surface depending upon density of interconnected fractures and scale of the investigation	Behaves as subsurface drains, which may be at, above, or below adjacent water table
Water level response to short-term recharge	Slow	Moderate	Rapid

Discrete Approach

The discrete approach is an attempt to evaluate ground-water flow in individual water-bearing fractures. Such an evaluation requires that fracture locations, density, orientation, interconnections, aperture, and channeling are accurately known (Long and Witherspoon, 1985; Barton and Hsieh, 1989). Once this information is measured and compiled, flow is simulated through the fracture network by use of a form of the cubic equation for flow through a parallel-walled fracture (Gale and others, 1985). At the field scale, complete knowledge of all fractures is very difficult to obtain. Therefore, this approach is useful chiefly to evaluate concepts, and it currently is not a practical approach for delineating a contributing area to a public-supply well.

Statistical Approach

The statistical approach acknowledges that a complete characterization of the physical properties of all fractures in a study area cannot be accomplished. Instead, the location, density, orientation, interconnections, aperture, and channelling properties of fractures are measured on a representative sample of the bedrock. The statistical distribution for each fracture characteristic is determined and transferred to form one possible representative fracture network at the field scale. Ground-water flow is then simulated through this fracture network. The network represents only one possible fracture pattern, but with the use of a fracture-generating computer program, many networks can be created with physical properties assigned according to their statistical probability. By simulating flow through many of these networks, a range of likely flow paths can be identified (Andersson and Dverstorp, 1987). The major difficulty with this approach is that the statistical distributions derived from the small sample of measured fractures may not apply at a larger scale. Recent research on the fractal nature of fractures (Barton and Larsen, 1985) indicates that fractal geometry can be used to guide the method for which fractures at the sample scale are transposed to the field scale. However, practical models on the basis of these methods are not presently used to delineate contributing areas to wells.

Continuum Approach

The most common method to analyze flow and estimate contributing areas for wells completed in fractured rocks is to treat the fractured bedrock as a porous-media continuum. For this substitution to be reasonable, the number of fractures and their interconnections must be numerous and distributed throughout the aquifer in the vicinity of the well field. However, unlike in a true porous medium, the number of individual fractures or fracture zones may be small relative to the spatial scale of the ground-water-flow system around the well field. Therefore, a representative volume of aquifer may not be found for which flow in individual fractures averages out sufficiently for the continuum approximation to be valid.

Evaluation of whether a fractured-rock aquifer can be approximated as a hydrologic continuum is a matter of temporal scale as well as spatial scale. Black (1989) argues that the geometry of the flow pattern to a well changes during pumping (fig. 3). For example, the early-time response of pumping from a fractured-rock aquifer may indicate one-dimensional (linear) flow through an individual fracture. At intermediate time, more fractures in the horizontal plane contribute to flow and flow becomes largely two dimensional and radial. At late time, pressure changes are propagated vertically through matrix or confining materials, possibly resulting in fully three-dimensional ground-water flow. Therefore, whether a fractured-rock aquifer can be approximated as a hydrologic continuum may depend on the time scale of the pumping. Black (1989, p. 11) also notes that the time scale required to achieve a hydraulic response of a given dimension is at least 10,000 times less than that for the actual mass transport of water. For example, the hydraulic response (indicated by water-level change) is fully three dimensional after about five log units of time; however, mass transport (indicated by transport of a tracer) is still responding in a one-dimensional manner (fig. 3). This lack of consistent dimension can lead to incorrect conclusions when evaluating tracer-test results.

Approximating a fractured-rock aquifer as a hydrologic continuum allows use of the analytical methods, such as the Theis equation, and mathematical models, such as MODFLOW, to quantitatively evaluate ground-water flow (Walton, 1988; van der Heijde and others, 1988). Because these are widely used and powerful methods, there is great incentive to apply the continuum assumption to an aquifer even when it is not warranted. Testing a fractured or conduit-flow aquifer to establish if it can be reasonably treated as a continuum is a subjective procedure usually based on the hydrologic experience of the investigator. Although there is no one definitive test for continuum response, several criteria can be used to provide an indication if the continuum approximation is reasonable. The U.S. Environmental Protection Agency (1991, p. 16) suggests that the fracture density, water-level configuration, water chemistry, hydraulic-conductivity distribution, and aquifer-test response can provide this subjective evidence.

Fracture Density.—Fractures should be numerous and widely distributed both horizontally and vertically throughout the likely contributing area. Fracture density can be evaluated by mapping, geophysical investigations, and borehole flowmetering. The U.S. Environmental Protection Agency (1991) suggests that the average distance between fractures should be at least 100 times smaller than the average distance to boundaries of the contributing area. Because most contributing-area boundaries will be on the order of thousands of feet from the well, fracture spacings should be on the order of tens of feet or less.

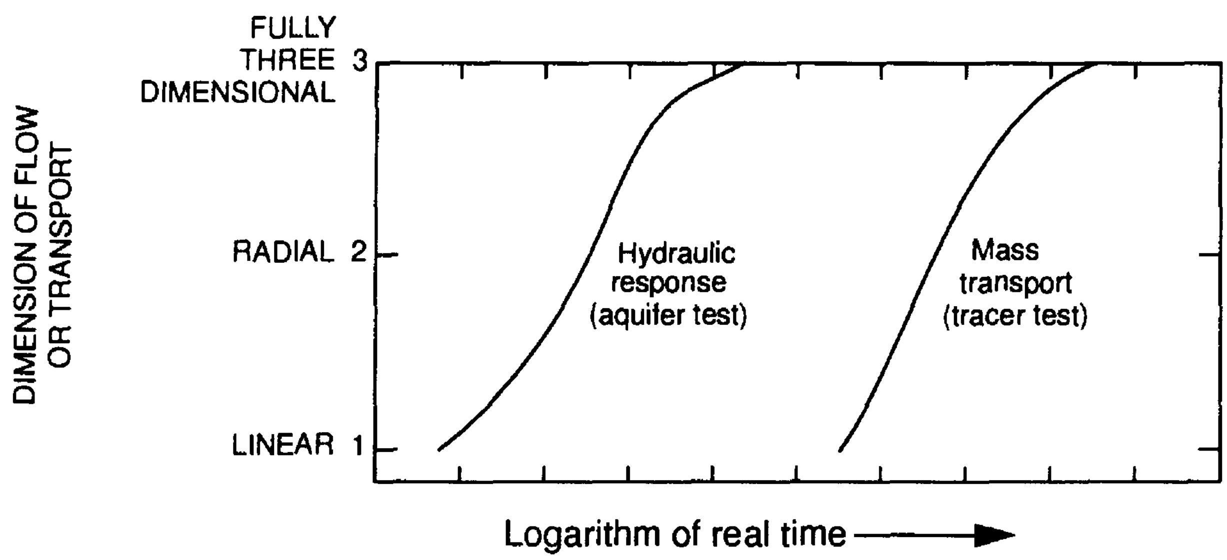

Figure 3. Change of dimension with time and its effect on aquifer and tracer tests. (Modified from Black, 1989, fig. 3.)

Water Levels.—Ground-water levels can be used in several ways to decide if a continuum approach is applicable. First, the water-level surface in the vicinity of the well field should be smooth and continuous. Anomalously high or low water levels in observation wells completed at the water-level surface could indicate hydraulic discontinuities, in which case the continuum approach is probably not appropriate. Second, if the water-level rise caused by uniform recharge differs greatly around the well field, a noncontinuum fracture network could be indicated.

Chemical Characteristics.—Diffuse flow in a hydrologic continuum in carbonate-rock terrains would be expected to produce water that is saturated or nearly saturated with respect to the dominant carbonate minerals encountered. Ground water that is greatly undersaturated with respect to calcite or dolomite probably indicates rapid, turbulent flow through a conduit or poorly integrated fracture network. Temporal variations in water-quality characteristics also are expected to be slight in aquifers that approximate a hydrologic continuum. Rapid changes during recharge events indicate that the continuum approach may not be warranted.

Hydraulic-Conductivity Distribution.—A sampling of hydraulic-conductivity values in an aquifer that approximates a porous medium should be log-normally distributed. According to the U.S. Environmental Protection Agency (1991), a distinctly bimodal distribution of hydraulic conductivity may indicate that the continuum approach is not applicable.

Aquifer Tests.—Aquifer tests provide the best evidence for accepting or rejecting the hydraulic-continuum approach. During a constant-discharge test, the cone of depression in a well field caused by pumping should be circular or elliptical in a hydrologic continuum. An extremely long, narrow drawdown cone probably indicates that a few unconnected fractures are providing water to the well. If the drawdown during a constant-discharge test plots linearly on a logarithmic graph of drawdown as a function of time, a noncontinuum approach is usually indicated. During a step-discharge test, a well commonly is pumped at various rates for about 1 hour per step. The drawdown in observation wells at the end of each step should plot linearly on an arithmetic graph (Hickey, 1984). A nonlinear plot indicates turbulent ground-water flow within the aquifer, which would certainly disqualify the continuum approach. Examples of some of these conditions are illustrated in U.S. Environmental Protection Agency (1991, fig. 6).

If the criteria described here indicate the hydrologic continuum approximation is reasonable, one of several standard methods (noting their inherent limitations and assumptions) can be used to delineate the contributing area to a well. The methods commonly used can be divided into five categories: fixed-radius, uniform-flow, analytical, semianalytical, and numerical-flow methods (U.S. Environmental Protection Agency, 1987; Javandel and others, 1984).

In many cases, some methods are likely to indicate the continuum approach is valid while others indicate that discrete fractures control ground-water flow. For example, the water-level drawdown caused by pumping might indicate flow through a linear fracture, even though the borehole-geophysical studies and flowmetering indicate a dense fracture network intercepted by the borehole throughout its depth. In such a case, simple analytical and semianalytical continuum methods that presuppose uniform aquifer properties may not be valid (Javandel and others, 1984). Instead, a distributed-parameter numerical model (McDonald and Harbaugh, 1988; Prickett and Lonnquist, 1971) might be appropriate if used to simulate ground-water flow by explicitly representing the major heterogeneities caused by fracturing.

Flow in Conduits

Conduit-flow systems are characteristic of karst terrains where fractures have been enlarged by dissolution of carbonate rocks. Ground-water flow is likely to be rapid, turbulent, and concentrated in discrete flow tubes and channels (table 2). The direction and velocity of ground-water flow in purely conduit-flow systems usually cannot be determined by use of standard analytical or modeling methods. Most investigations of these systems rely chiefly on dye tracing to characterize subsurface hydraulic conditions (Mull and others, 1988).

Ground-water flow in most carbonate aquifers does not occur exclusively in conduits. More commonly, conduits exist within a larger network of fractures that, at a large scale, may approximate a hydrologic continuum. In such cases, numerical-flow models have been successfully used in Pennsylvania to simulate some aspects of the ground-water-flow system (Sloto, 1990).

STRATEGY FOR DELINEATING A CONTRIBUTING AREA

Delineation of a contributing area to a well completed in a fractured bedrock aquifer in Pennsylvania is usually difficult because the hydrogeologic characteristics of fractured rocks are extremely complex. Because of this complexity, a single method or technique to delineate a contributing area will not be applicable for all wells completed in fractured-bedrock aquifers. Therefore, rather than presenting a method to delineate contributing areas, a strategy for refining the understanding of boundary conditions and major heterogeneities that control ground-water flow and sources of water to a supply well is suggested. An improved understanding of the ground-water-flow system will lead to a technically defensible delineation of the contributing area.

The strategy to delineate contributing areas in bedrock aquifers is summarized in figure 4. It is based on developing and refining a conceptual model for the sources of water to the well. Specifically, the strategy begins with an initial conceptual model of the ground-water-flow system, then requires the collection of hydrogeologic information to refine the conceptual model in a stepwise manner. During the refinement process, the applicability of treating the fractured-rock aquifer as a hydrologic continuum is evaluated, and the contributing area is delineated by use of a method consistent with the refined conceptual model of the hydrologic system. Individual elements of the strategy are discussed further in the following sections.

Initial Conceptual Model

Under the proposed strategy, the evaluation begins with a conceptual model of the sources of water to the well (fig. 4) that is based on a literature review of general hydrogeologic conditions near the well. The conceptual model is a formulation of how ground water moves from recharge areas to the well. It should include a quantification of the hydrogeologic framework, boundary conditions, and internal hydraulic properties of the aquifer (table 3). Sketching the possible sources or formulating a budget is also an important part of the conceptual-model development that leads to the delineation of a contributing area. The first approximation of the conceptual model may be very crude if the hydrogeology of the area is unknown, or it may be fairly sophisticated if the hydrogeology is well defined.

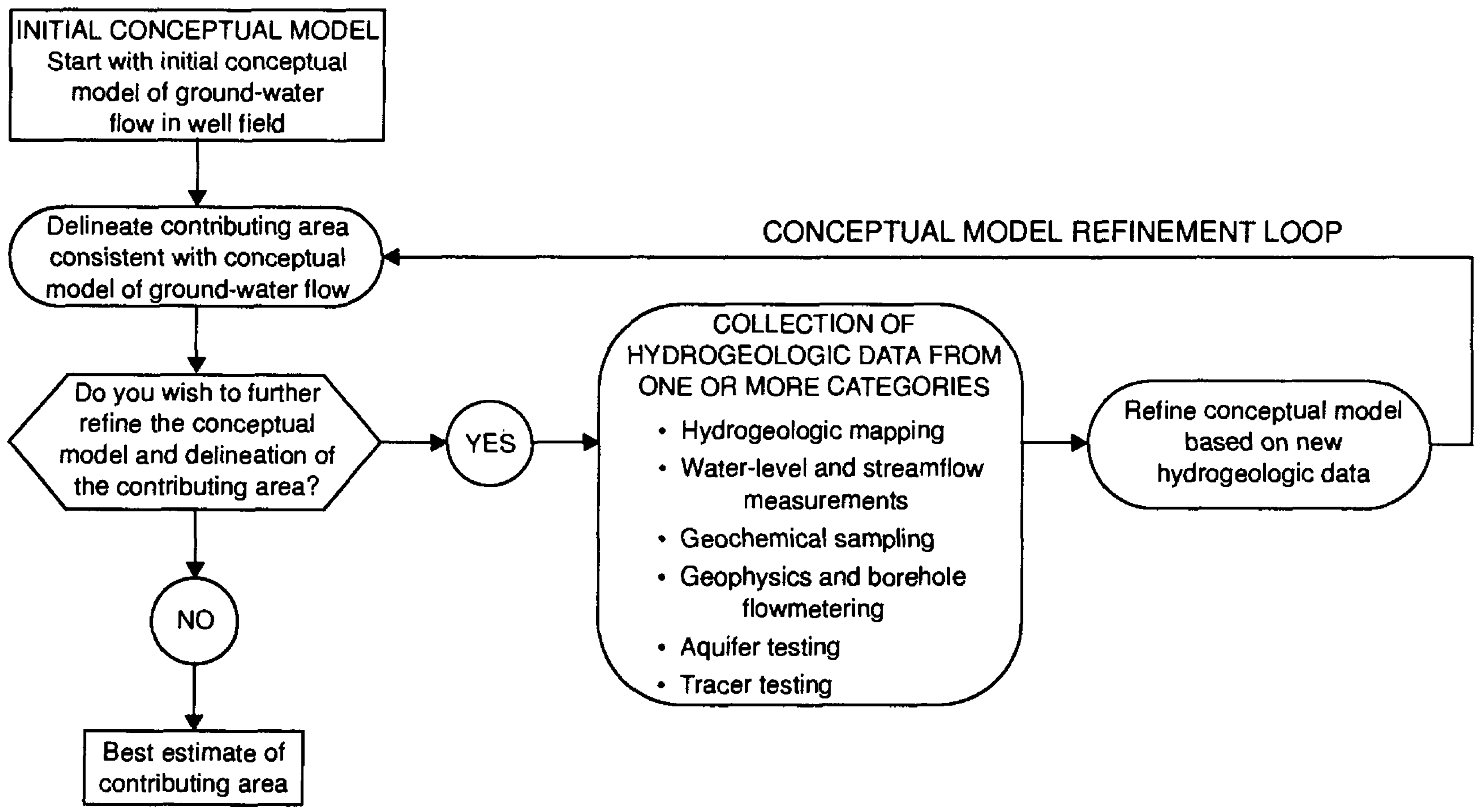

Figure 4. Overall strategy for delineating contributing areas in bedrock aquifers.

Table 3. *Information needed to develop a conceptual model of a fractured-rock aquifer*

Category of information needed	Specific data needed
Hydrogeologic framework →	① Lateral and vertical extent of aquifer or water-bearing zones
	② Identify fractures yielding water to the well
Boundary conditions →	① Locate hydrologic barriers to ground-water flow
	② Locate streams and other surface-water bodies and quantify flow between the aquifer and these boundaries
	③ Define water-table configuration and quantify recharge across this boundary
	④ Locate wells, springs, and other discharge boundaries and quantify flow from aquifer
Internal hydraulic properties →	① Estimate horizontal and vertical hydraulic conductivity; define major heterogeneities
	② Estimate storage coefficient and specific yield
	③ Estimate aquifer porosity

Delineation Methods

After an initial conceptual model has been formulated, an estimate of the contributing area can be delineated, even if the hydrogeologic framework, boundary conditions, and aquifer properties of the system are mostly conjecture. The actual method used to delineate the contributing area is less important than making sure that the method is consistent with the conceptual model. For example, if the initial conceptual model formulation indicates that a nearby stream is likely to be an important source of water induced by the well, the method to delineate a contributing area should be able to account for that complexity. Commonly, however, technical or financial resources will not be available to apply the method of sophistication appropriate to the complexity of the conceptual model. In these cases, the conceptual model will allow the investigator to recognize the possible weaknesses in the delineation so the results can be reported with appropriate caveats.

Delineation methods should attempt to incorporate the major heterogeneities within the fractured-bedrock aquifer. As discussed earlier, the complete three-dimensional fracture-flow network will be impossible to determine; however, any major fractures or fracture concentrations that are found by hydrogeologic investigations to greatly influence ground-water flow can be incorporated in numerical models. Numerical models assume that ground-water flow in fractures approximates that in a hydrologic continuum, but by explicitly incorporating the major heterogeneities in the model by use of zones of differing hydraulic properties, the model can sometimes capture the essence of a flow system where a few fractures are important and a strict continuum of flow is not observed. A hypothetical example of the use of a numerical model that incorporates major heterogeneities is shown in figure 5.

The numerical modeling of heterogeneities can provide a fairly reasonable simulation of hydraulic heads and flux through a fractured-bedrock aquifer, which allows an area of diversion (PaDER wellhead Zone II) to be delineated. Delineation of a time-of-travel area, however, requires that the velocity field within the aquifer can be simulated. Simulating the velocity field requires knowledge of the effective porosity or fracture apertures throughout the aquifer, which are usually not known unless tracer tests have been conducted. Thus, any time-of-travel simulations in fractured rocks should be viewed as very coarse estimates unless verified with tracer tests.

Methods used to delineate a contributing area can be categorized as continuum methods, if fractures are assumed to approximate a hydrologic continuum, and noncontinuum methods, if the method is applicable regardless of the interconnectedness of fractures. These methods are presented in detail in several reports (U.S. Environmental Protection Agency, 1987, 1991; Risser and Madden, 1994). Characteristics of selected continuum methods are compared in table 4. The fixed radius, uniform flow, analytical, semianalytical, and flow-system mapping methods are simpler to apply but less able than numerical modeling to simulate complex boundary conditions and heterogeneities that commonly are important elements of fractured-bedrock aquifers.

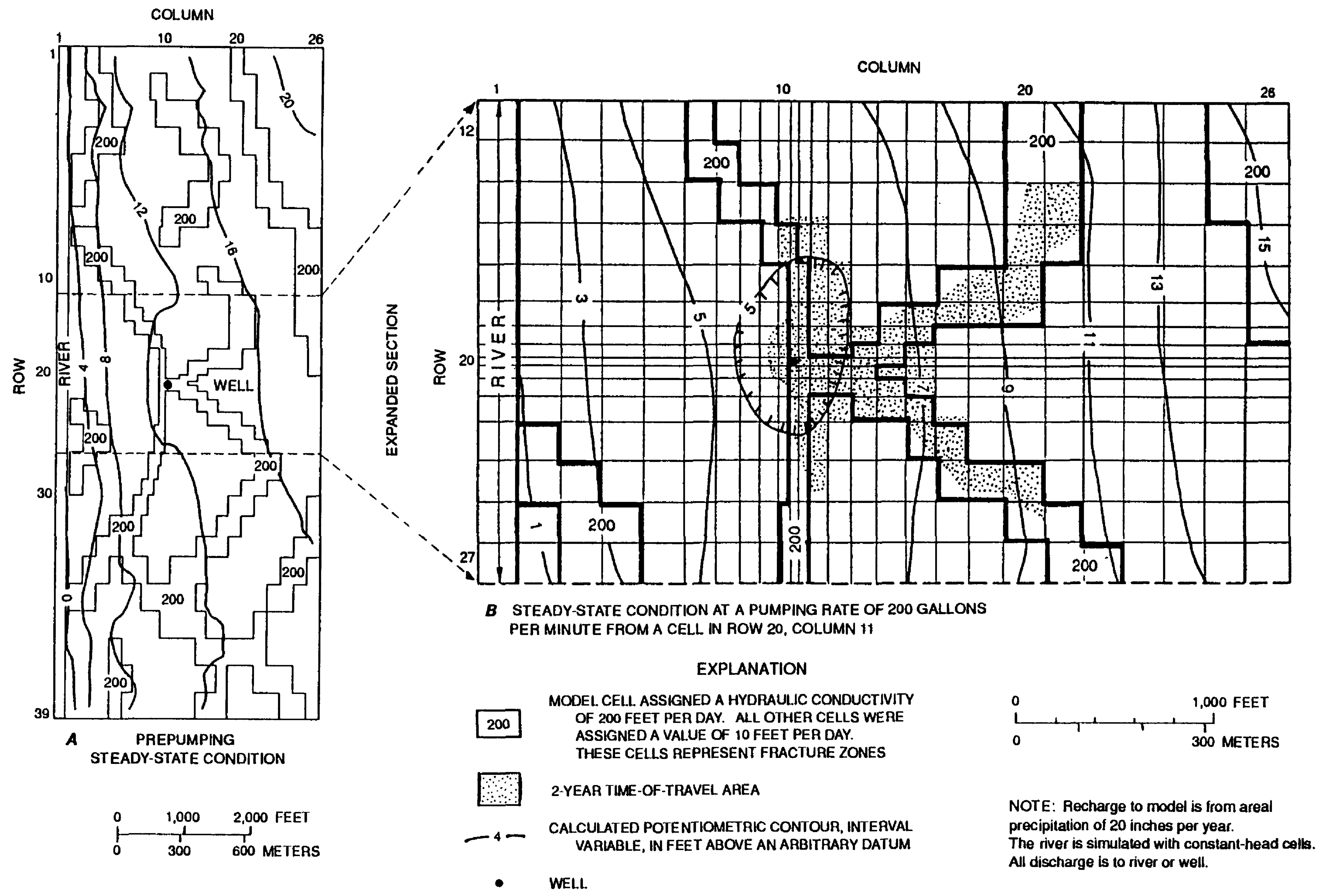

Figure 5. Example of use of a numerical model to simulate an aquifer with heterogeneous fracture zones.

Table 4. *Major assumptions inherent in selected continuum methods for delineation of contributing area*

[2-D, two-dimensional; 3-D, three-dimensional]

Hydrologic factors	Methods					
	Fixed radius	Uniform flow	Analytical	Flow-system mapping	Two-dimensional semianalytical	Three-dimensional numerical-flow modeling
Aquifer type	Confined [1] 2-D	Confined [1] 2-D	Confined [1] 2-D	Confined or unconfined 2-D	Confined [1] 2-D	Confined or unconfined 3-D
Thickness	Uniform	Uniform	Uniform	Uniform	Uniform	Variable
Potentiometric surface	Flat [2]	Uniform	Measured	Measured	Uniform	Measured
Aquifer properties	Homogeneous and isotropic horizontally and vertically	Homogeneous and isotropic horizontally and vertically	Homogeneous and isotropic horizontally and vertically [2]	Homogeneous and isotropic horizontally and vertically	Homogeneous and isotropic horizontally and vertically	Heterogeneous and anisotropic vertically and horizontally
Boundary conditions	None	None	Linear and fully penetrating	Irregular geometry, fully penetrating	Linear and fully penetrating	Irregular geometry, partially penetrating
Recharge	None or uniform	None	None or uniform	Variable	None	Variable
Well characteristics	Fully penetrating single well	Fully penetrating single well	Fully or partially penetrating single well	Fully penetrating single or multiple wells	Fully penetrating single or multiple wells	Fully or partially penetrating single or multiple wells
Type of area delineated	Time-of-travel area	Time-of-travel area or area of diversion	Area of diversion only	Time-of-travel area or area of diversion	Time-of-travel area or area of diversion	Time-of-travel area or area of diversion

[1] Unconfined aquifer can be simulated if drawdown is less than 10 percent of saturated thickness.

[2] *Depends on analytical equation used.*

Noncontinuum methods are based on geochemical information or results from tracer experiments. A residence-time method uses age-dating of ground water and geochemistry to approximate the aquifer volume through which water is likely to be contributed to the supply well (U.S. Environmental Protection Agency, 1991, p. 44). Geochemical methods are rarely able in themselves to provide enough unambiguous information for delineation of an accurate contributing area or time-of-travel area. They are most effectively used in conjunction with continuum methods. Tracers injected into the aquifer or environmental contaminants that can be traced to specific source areas provide another noncontinuum method to delineate contributing areas. Tracers, especially in karst terrain, provide direct verification of the area of contribution and time-of-travel area without assumptions about the continuum nature of the fractured bedrock.

Refining the Conceptual Model

Refining the conceptual model is the major part of the proposed strategy illustrated in figure 4 for delineating contributing areas. The initial conceptual model can be refined in a stepwise manner by use of hydrogeologic information collected during investigation at the well field. Methods that should be considered as part of the well-field investigation are listed in six categories: hydrogeologic mapping, water-level and streamflow measurements, geochemical sampling, geophysics and borehole flowmetering, aquifer testing, and tracer testing (table 5).

Table 5 shows three general levels of difficulty to collect and interpret these data. Field investigations usually should begin with data that are easy to collect and interpret and move to more difficult data collection on the basis of the data needs revealed by the revised conceptual model. Hydrogeologic methods useful for refining the conceptual model are described by category in the following sections.

Hydrogeologic Mapping

Maps of the topography, geology, fractures, and water-level distribution help define the hydrogeologic framework of the aquifer and thus constrain the extent of the contributing area. In addition, maps of fractures and water levels may indicate if the bedrock aquifer is likely to act as a hydrologic continuum.

Topographic and Physiographic Mapping

Topographic maps of the watershed can be used to delineate a first approximation of the contributing area for a well in the watershed. By assuming that the ground-water basin coincides with the topographic basin, the contributing area for a well that produces from shallow water-bearing zones (less than about 200 feet deep) is likely to lie within the watershed. If the ground-water basin boundaries differ from the surface watershed boundaries, as is typical in carbonate terrains where conduits provide pathways beneath topographic divides (Becher and Root, 1981; Quinlan, 1989), the contributing-area boundaries must be adjusted to the position of the ground-water basin boundaries. Topographic maps also are needed to locate streams, swamps, and lakes that are potential sources of induced infiltration to the well. In cases where a water-level contour map is not available, water-level contours sometimes can be sketched as a subdued representation of the surface topography (Battaglin and others, 1989, p. 531-539).

Geologic Mapping

Geologic maps can provide information on possible physical constraints and preferred avenues of ground-water flow. Dikes and sills, lithologic changes, folds, faults, and other geologic features can control ground-water-flow paths by changing the hydraulic conductivity of the aquifer (Davis and DeWiest, 1966). The rocks dip steeply in many parts of the Ridge and Valley and the Piedmont Physiographic Provinces of Pennsylvania; thus, they generally exhibit a high degree of anisotropy, with the greatest value of hydraulic conductivity parallel to strike. Geologic maps also can be used to assign properties such as hydraulic conductivity and specific yield to rocks in the vicinity of the well field. Approximate values of these properties commonly can be obtained from the literature for specific lithologies or geologic formations.

Table 5. *Hydrogeologic methods useful for refining the conceptual model of ground-water flow to a well*

Method category	Data provided	Complexity of collection and analysis	Focus of information obtained				
			Hydrogeologic framework	Aquifer properties	Boundary conditions	Direct evidence of water source	Evaluation if fractures approximate a continuum
1 Hydrogeologic mapping							
1A	Topographic and physiographic	Low	X		X		
1B	Geologic	Low	X		X		
1C	Fractures, sinkholes, and lineament delineation	Low	X				X
1D	Water-table configuration	Low	X	X	X		X
2 Water-level and streamflow measurements							
2A	Ground-water level changes caused by pumping or recharge	Moderate	X	X	X		X
2B	Streamflow measurements	Moderate			X		
3 Geochemical sampling							
3A	Chemical differences of water sources	Low			X	X	
3B	Age dating	High	X	X			
3C	Mineral saturation	Moderate	X			X	X
3D	Seasonal variations	Moderate		X			X
4 Geophysics and borehole flowmetering							
4A	Surface-geophysical surveys	High	X	X	X		
4B	Borehole logging	Moderate	X				X
4C	Borehole flowmetering	High	X	X			
5 Aquifer testing							
5A	Slug tests	Moderate		X			X
5B	Constant-discharge tests	Moderate		X	X		X
5C	Step-discharge tests	Moderate		X			X
6 Tracer testing							
6A	Single-well tests	High		X		X	
6B	Multiple-well tests	High		X	X	X	X

Fractures, Sinkholes, and Lineaments

Maps of features, such as fractures, sinkholes, and lineaments, provide information on the density and orientation of fractures. Plotted on a rose diagram or stereonet, the orientation of these features provides an indication of the principal directions of anisotropy. The density and orientation of fractures can be used as qualitative evidence that a fractured-rock aquifer is or is not likely to approximate a hydrologic continuum. According to the U.S. Environmental Protection Agency (1991), the average distance between fractures should be at least 100 times smaller than the average distance to boundaries of the contributing area for the fractures to approximate a hydrologic continuum.

Secondary-permeability features may be preferred avenues of ground-water flow. Thus, identification of a few major fractures could be the key to understanding the source of ground water to a well.

Water Table

A water-table map provides information on flow directions, head gradients, and the location of ground-water divides. The divides can be mapped as probable limits of contributing areas for wells in that basin, although their position can be shifted by nearby pumping wells (Risser and Madden, 1994). The water-table configuration sometimes is a clue to a discontinuous, poorly connected fracture system if water levels in some wells do not fit the expected distribution. For example, a graph of water-level altitude in wells as a function of land-surface elevation should plot as a smooth curve. Outliers from that curve could indicate discontinuities in the flow system. Also, the nonpumping regional water-level slope is needed to delineate a well's contributing area by several analytical methods.

Water-Level and Streamflow Measurements

Water-level fluctuations can provide valuable, although subjective, information on fracture interconnections laterally and with depth. Streamflow measurements can provide important estimates of recharge to ground water.

Ground-Water Fluctuations Caused by Precipitation

Ground-water-level fluctuations resulting from individual storms can be analyzed to help evaluate if fractures are interconnected as a conduit or diffuse-flow system (White, 1988). Conduit systems are characterized by rapid water-level increases during aquifer recharge, whereas diffuse-flow systems typically exhibit a subdued and delayed water-level response. Water-level changes in karst aquifers may be tens of meters in a few hours (White, 1988, p. 183). Such rapid water-level fluctuations suggest that hydrologic-continuum methods may not be appropriate for delineation of a contributing area.

Ground-Water Fluctuations Caused by Pumping

Ground-water pumping causes water-level changes that can be predicted reliably if the bedrock aquifer approximates a continuum. A relatively homogeneous continuum is indicated if water levels decline in all observation wells within the area of pumping influence, and the greatest declines are nearest the pumped well. An anisotropic continuum may be indicated if water levels in all observation wells decline, but the response is greatest at some distant wells. If water levels in some observation wells do not decline in response to pumping, while levels in other nearby wells decline, a poorly connected fracture network probably is present.

Care must be used when assigning significance to the observed water-level fluctuations in wells. For example, during pumping of a well, drawdown measured at an observation well does not necessarily indicate that water at the observation well is moving toward the pumped well, as the observation well location may or may not be within the pumped well's area of diversion (Morrissey, 1987). The drawdown does, however, indicate a hydraulic connection that helps evaluate the heterogeneity and anisotropy of the aquifer.

Recharge Estimates from Streamflow Measurements

Streamflow measurements at a streamflow-gaging station can be used to estimate the base-flow component of runoff (Rutledge, 1993). The average annual base flow is commonly assumed to represent average recharge to the aquifer throughout the basin. From the average recharge rate, a simple water budget can be constructed to estimate the maximum steady-state extent of the area of diversion to a shallow well. By equating the well's pumping rate to the estimated rate of recharge on the surface of its contributing area, the area of diversion can be computed as follows:

$$A = (843{,}200)\ Q/R\ , \qquad (1)$$

where A is steady-state area of diversion, in square feet;
Q is pumping rate, in gallons per minute;
R is ground-water recharge, in inches per year; and
843,200 is a factor to convert the answer to square feet.

The water-budget computation provides an approximate *area of diversion*, which is the projected area on the aquifer surface through which recharge actually moves to the well. The area of diversion can be much smaller than the area indicated by this method if infiltration from nearby surface-water sources is induced by pumping. Because the pumped water may have come from sources other than recharge directly from precipitation on the aquifer surface (such as induced infiltration of surface water), the *contributing area* could include the entire drainage basin of the surface-water source (an area possibly much larger than that computed by the water-budget method). The water-budget computation of area of diversion also is likely to be in error for wells completed in confined aquifers and multi-aquifer systems, or for partially penetrating wells completed in vertically anisotropic aquifers (Risser and Madden, 1994, p. 55).

A simple example illustrates application of the water-budget estimate. In a watershed within the carbonate rocks of the Ridge and Valley Physiographic Province of Pennsylvania, base-flow discharge during 1968-74 comprised about 76 percent of the total runoff of 20 inches per year (Becher and Root, 1981, p. 12). Assuming that base flow is equal to recharge, recharge would average about 15 inches per year. On the basis of equation (1), the approximate area of diversion for a well that pumps 500 gallons per minute is about 28 million square feet—a little more than 1 square mile—assuming that recharge across the aquifer surface is the only source of recharge to the aquifer that reaches the well. The water-budget estimate, however, does not provide any information on the location of the area of diversion.

Geochemistry

Information on ground-water chemistry can help in the evaluation of the source of water to the production well. In addition, geochemical information may provide clues to whether flow predominately is in conduits, isolated fractures, or in a diffuse continuum of fractures and pores.

Chemical Differences of Source Water

The type and concentration of solutes in ground water can be used to help evaluate the sources of recharge and potential travel paths. Natural inorganic constituents in the water provide information on rock units in which the ground water has been in contact. Inorganic constituents in ground water can be compared graphically by use of trilinear plots (Piper, 1944) or Stiff diagrams (Davis and DeWiest, 1966). More quantitative information can be obtained by evaluating changes of inorganic constituents along possible flow paths by the use of speciation and mass-balance computer programs such as those by Truesdell and Jones (1974) and Parkhurst and others (1980; 1982).

Contaminants also can be used to identify potential sources of recharge and ground-water-flow paths. Man-made organic contaminants, such as halogenated hydrocarbons, herbicides, and insecticides, indicate relatively recent recharge, the source of which may be evident on the basis of knowledge of local uses of these compounds. Elevated concentrations of nitrate, ammonia, bacteria, or chloride may indicate local recharge affected by agriculture, wastewater, or road salt (Berner and Berner, 1987). Optical brighteners, surfactants, and trihalomethanes also may indicate a wastewater source—either municipal or individual septic systems (Glover, 1972; Thurman, 1985, p. 226). Maps showing local sources of contaminants may help identify likely ground-water travel paths and contributing areas to wells.

Age Dating

Age dating of water from wells located throughout a supply well's contributing area can help quantify traveltime to the supply well. Contaminants indicate a source of recharge no older than the occurrence of the contamination, but other stable compounds and radionuclides can be used to estimate the chronological age of recharge (Davis and Murphy, 1987). Chlorofluorocarbons are very stable anthropogenic contaminants that have recently been used to date waters younger than about 1940 (Plummer and others, 1993, p. 253). Commonly used radioisotopes include tritium and carbon-14. The presence of tritium, which was produced in large concentrations by atmospheric nuclear tests, indicates the recharge is less than about 50 years old. Carbon-14 can be used to date waters that recharged the aquifer from about 500 to 30,000 years before present. Other less commonly used radionuclides include silicon-32, chlorine-36, argon-39, krypton-85, and iodine-127 (Davis and others, 1985). Stable isotopes of oxygen and hydrogen commonly are used to identify waters recharged during a past climatic regime or to distinguish a surface-water source from a ground-water source (Gat and Gonfiantini, 1981). Because concentrations of oxygen and hydrogen isotopes vary seasonally and throughout a storm event, analysis of many water samples collected over several months would be needed to help evaluate a contributing area to a well.

Water-bearing fractures and conduits intersecting a well at different depths may yield water of different ages, which implies that the well is open to a multi-aquifer system and that each aquifer may have a different contributing area. Water from a well open to a multi-aquifer system may be a mixture from all water-bearing fractures. Therefore, a water sample may not represent conditions in any individual aquifer. For example, in the case of age dating by use of tritium, recent water from a shallow aquifer may have a tritium concentration of 20 tritium units, and older water from a deeper confined zone may have no detectable tritium. If a well is open to both zones and the two zones contributed equal amounts of water to the well during pumping, the resulting water sample would have a tritium concentration of 10 tritium units. The erroneous conclusion that could be drawn from this single sample is that all the water is relatively young and the contributing area surrounds the well. Isolation of the older water from the deeper zone (that likely was contributed at greater distance) would require use of straddle packers so that water from individual fractures could be sampled separately.

Mineral Saturation

In a carbonate terrain, ground water that is not saturated or nearly saturated with respect to the predominant carbonate mineral probably indicates rapid transport in a conduit-type flow system. In addition, analysis of the major inorganic solutes, carbon isotopes, and pH can indicate if the carbonate rock was dissolved in a system open or closed to the atmosphere (Langmuir, 1971). Shallow conduit-flow systems are generally open to atmospheric gases, while deeper diffuse-flow systems may be closed.

Seasonal Variations

Changes in major-ion chemistry, dissolved oxygen, temperature, and pH of ground water may help distinguish between a conduit-flow and a diffuse-flow system. Sudden changes after precipitation indicate conduit flow, whereas subdued changes indicate diffuse flow (Shuster and White, 1971). For example, on the basis of seasonal variations in water temperature, Hippe and others (1994) classified Mount Rock and Alexanders Springs as diffuse flow and SP-33 and SP-34 as conduit flow (fig. 6).

Geophysics and Borehole Flowmetering

Surface- and borehole-geophysical techniques measure contrasts in physical and chemical properties of soil, ground water, and rocks, such as their seismic velocity, density, magnetic-field intensity, electrical conductivity, thermal conductivity, and natural radioactivity. The techniques require measurement of natural or artificial signals, such as gamma radiation emitted from soils and rocks or a field induced by an electric current. Borehole flowmetering is the direct measurement of vertical flow of fluid within a well.

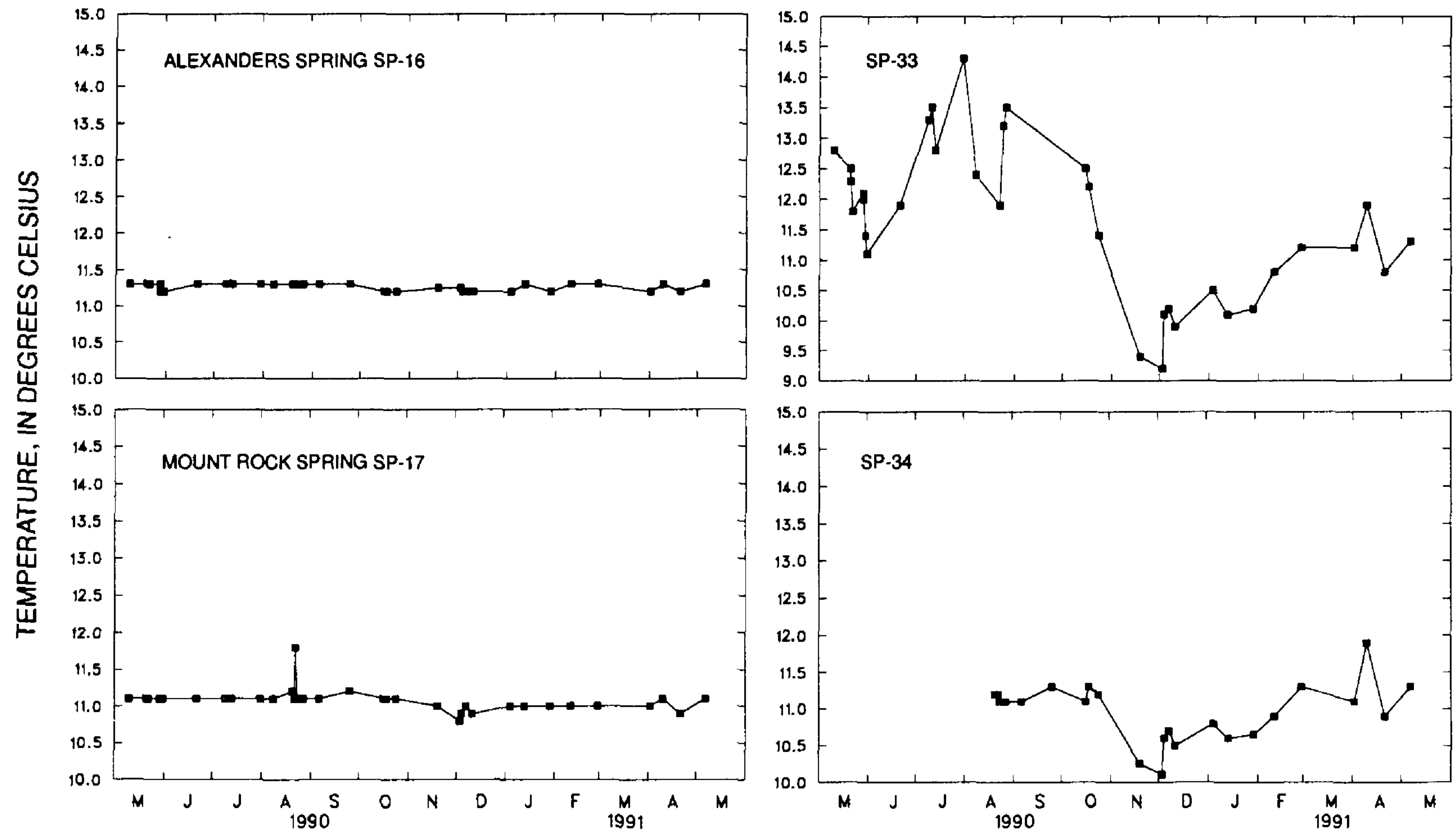

Figure 6. Temperature of water from Alexanders Spring, Mount Rock Spring, Spring 33, and Spring 34 in central Pennsylvania (from Hippe and others, 1994, fig. 5).

Surface Geophysical Surveys

Surface-geophysical surveys can aid aquifer-framework analysis by providing estimates of the strike of vertical fractures and by identifying of subsurface cavities. Currently, the ability of surface-geophysical techniques to identify horizontal fractures or subhorizontal fractures is technologically limited. Surface-geophysical surveys of bedrock terrain are useful for augmenting hydrogeologic mapping, where data from boreholes and outcrops are sparse. Examples of conventional surface-geophysical surveys include (1) seismic refraction for mapping the thickness of colluvium or glacial material (Haeni, 1986), (2) magnetic studies for mapping fracture-alteration zones and dikes that act as no-flow boundaries (Telford and others, 1976), and (3) azimuthal resistivity (Taylor and Flemming, 1988), azimuthal refraction, and azimuthal electromagnetic-terrain-conductivity surveys for mapping the strike of vertical fractures and estimating aquifer anisotropy.

An annotated bibliography of surface-geophysical techniques to detect fractures in bedrock is included in Lewis and Haeni (1987). Conventional techniques for hydrologic applications are discussed by Zohdy and others (1984).

Borehole-Geophysical Logging

Borehole-geophysical logging can significantly aid lithologic analysis, fracture characterization, analysis of hydraulic properties, and evaluation of well construction. Borehole-geophysical logging, in conjunction with surface-geophysical surveys, geologic mapping, and aerial-photo analysis, adds a third dimension to the characterization of lithology and fractures. Rock exposures (road cuts, quarry walls, or natural outcrops) provide some information that borehole-geophysical logs provide. However, these exposures are commonly limited in number and may be altered by anthropogenic activities or natural weathering processes. Borehole-geophysical logs can be used effectively in evaluating contributing areas because they can (1) characterize the lithology, fracture geometry, water-bearing zones, and vertical head gradients in and near a well; (2) provide data for additional borehole investigations, such as identifying zones to set straddle packers; and (3) be collected relatively inexpensively compared to many other hydrologic methods.

Care must be used when correlating logs from well to well. Mapping fractures from well to well is difficult because fractures are generally planar to curvi-planar and linear to nonlinear with widely variable lengths (Barton and Hsieh, 1989). In addition, topographic relief, dipping strata, and well depth may limit correlation of logs between wells.

Conventional geophysical-logging measurements are described by Keys (1990). A detailed bibliography of borehole geophysics as applied to ground-water hydrology is given by Taylor and Dey (1985). Conventional and unconventional borehole-logging methods are summarized below.

Many relatively inexpensive logs are available for studying lithology. Ground-water studies commonly rely on conventional logs such as caliper, single-point resistance, calibrated resistivity, self-potential, and gamma-ray logs (Barton and Ivahnenko, 1991).

Several inexpensive conventional logs also can be used to study the geometry of fractures intersected by a borehole. Caliper, single-point resistance, and gamma-ray logs are commonly used for identifying fractures. These logs may identify selected fractures and provide an estimate of the occurrence of fractures with depth. However, these logs provide little information about the geometry of fractures in the formation. Television logging, especially if equipped with a compass for orientation, is becoming popular and may provide more detail about fracture geometry than the previously mentioned conventional logs. Television logging is particularly useful in identifying subvertical or vertical fracturing. Comparatively expensive unconventional logs, such as full-waveform acoustic, acoustic televiewer (Paillet, 1985), vertical-seismic profiling (Hardin and Cheng, 1987), borehole radar, and resistivity tomography may provide good estimates of fracture geometry at greater distances from the wellbore.

Borehole-Vertical Flowmetering

Relatively inexpensive flowmetering, such as brine tracing (Patten and Bennett, 1962), impeller techniques (Keys and MacCary, 1981), and heat-pulse techniques (Keys, 1990), can be used to measure vertical flow in a borehole. Brine tracing, the most common and simplest flowmetering method, requires only a fluid-resistance or conductance tool and equipment to inject brine slugs at selected depths in a well. By timing the vertical displacement of the brine slug, vertical fluid velocities in the borehole as low as 0.5 feet per minute can be detected. These flowmeter methods are used to identify water-bearing zones and characterize vertical-hydraulic gradients. The yield and horizontal hydraulic conductivity of water-bearing zones may be estimated by use of simultaneous flowmetering and constant ground-water injections or withdrawals in a well (Morin and others, 1988; Moltz and others, 1990). For example, by flowmetering at various depths in the borehole while pumping water from the well, the cumulative yield of the aquifer is determined at those depths. The yield from a specific zone is simply the difference between the flow measurements straddling that zone. If the radial gradient along the well bore is constant and uniform, the transmissivity of that water-bearing zone is proportional to its yield (Moltz and others, 1990, p. 14).

Vertical flow of water between fractures in a well indicates that multiple water-bearing and receiving zones are present. Individual fractures or fracture sets with different hydraulic heads may or may not have different contributing areas. Typically, the contributing area for a confined aquifer is more distant from the well than that for the overlying unconfined aquifer. Therefore, the approach for delineating a contributing area ideally should include an evaluation of each zone that contributes water to the well.

Aquifer Testing

Aquifer tests are conducted by pumping the aquifer and observing the water-level response to that stress. They are chiefly used for determining aquifer properties and evaluating boundary conditions, but the tests also can help indicate the degree of fracture interconnections, aquifer heterogeneity, and anisotropy with respect to hydraulic properties. In general, the amount of information that can be obtained from an aquifer test depends on the number of observation wells available. As a general rule, at least one well is needed for each hydraulic characteristic to be determined. For example, transmissivity (or hydraulic conductivity) can be determined from drawdown in the pumped well. Two wells are needed to evaluate the storage coefficient. Vertical hydraulic conductivity requires a third well. To determine anisotropy, four wells are usually needed.

Estimates of aquifer properties are required for most quantitative methods to evaluate the contributing area to a well. Several authors discuss standard aquifer-test methods in detail (Lohman, 1972; Walton, 1988; Kruseman and de Ridder, 1976; Reed, 1980; Driscoll, 1986). A new approach to measure the vertical variation of horizontal hydraulic conductivity by use of aquifer testing is suggested by Molz and others (1990). This approach, which involves pumping and simultaneous borehole flowmetering, can provide essential information about fracture interconnections and likely pathways of ground-water flow that cannot be determined with standard methods. Some commonly used aquifer-testing methods are listed below.

Slug Tests

Slug tests provide a quick and inexpensive method of estimating aquifer hydraulic conductivity or transmissivity in the immediate vicinity of a well. Slug tests are conducted by suddenly changing the water level in a well by use of a bailer, displacement barrel, or compressed gas (Prosser, 1981). The resulting water-level change with time is monitored in the same well and can be analyzed by use of several methods (Bouwer and Rice, 1976; Cooper and others, 1967; Papadopulos and others, 1973, Hvorslev, 1951; van der Kamp, 1976; Kipp, 1985). By conducting these tests in several wells or at vertical intervals within a single well by use of packers, the spatial distribution of hydraulic conductivity and any associated heterogeneity can be evaluated (Molz and others, 1990).

Step-Discharge Tests

Step-discharge aquifer tests are conducted by pumping a well at increasing rates in a stepwise manner. Step-discharge pumping tests usually are conducted to evaluate the optimum pumping rate for a public-supply well. The tests also provide an indication of the amount of turbulent flow in the aquifer around the pumped well (Driscoll, 1986) and, at greater distances, into the aquifer. Turbulence at observation wells located tens of feet or more from the pumped well, if indicated by the step-testing analysis of Hickey (1984), means that the assumption of laminar flow, inherent in all porous-continuum methods, is not valid. The step test for turbulence at observation wells is conducted by pumping the supply well in steps and recording drawdown in nearby observation wells.

Constant-Discharge Tests

Constant-discharge aquifer tests are conducted by pumping a well at a constant rate and measuring water-level declines in the pumped well and any available observation wells. Many test designs and analysis methods are available to evaluate aquifer properties and boundary conditions (Lohman, 1972; Kruseman and de Ridder, 1976). Constant-discharge tests can help evaluate if the fractured-rock aquifer approximates a hydraulic continuum. The U.S. Environmental Protection Agency (1991) states that for a hydraulic continuum, the cone of depression should be circular for isotropic aquifers and elliptical for anisotropic aquifers, and the time-drawdown plots for observation wells should have similar shapes without sharp changes in slope.

Packers are useful for investigating possible fracture connections between wells. In the pumped well, straddle packers can be used to isolate individual fractures so they can be separately stressed. The drawdown caused by pumping can be measured in observation wells where fractures also are isolated by use of packers. Examples of these techniques are presented in Molz and others (1990).

Tracer Testing

Tracers are by far the most conclusive method for evaluating the direction and traveltime of ground-water flow in bedrock aquifers. Tracer tests are conducted by injecting a tracer, such as organic dye, inorganic salt, gas, or solid particles (Davis and others, 1980), into the aquifer at a natural opening or well, then monitoring its arrival at a nearby spring or well. Analysis of the results of tracer tests are conceptually straightforward; tracer recovery at a given location indicates a hydraulic connection, and the time required to detect the tracer provides information on ground-water velocities. Tracers are most commonly used in karst terranes, where conduits provide avenues for rapid ground-water flow. Although tracers are powerful tools, they are not easy to use in all hydrogeologic settings. Because ground-water flow is generally slow in nonkarst aquifers, tracer tests commonly require months or years to establish flow paths of only tens or hundreds of feet. If dye is not detected at an observation point during a certain time period, questions arise concerning the connection of the observation point to the injection point and the length of the observation period. Except in karst areas, natural surface features to inject and recover dye generally are not available; thus, wells, which may or may not intersect the fractures of interest, will be needed for the testing program.

Some tracers may pose health or aesthetic problems. The introduction of tracers into an aquifer must be conducted with careful consideration of such possible implications. Studies that use artificially introduced tracers should have advance approval from local or state authorities, and, as appropriate, local ground-water users should be informed of the testing program (Quinlan, 1989).

The most common use of tracers is in karst terrains to evaluate the physical connections and traveltimes of ground water between sinkholes and springs (Mull and others, 1988; Quinlan, 1989; Aley and Fletcher, 1976). Tracers work well in these terrains because ground-water-flow velocities are relatively high, and connections over great distances can be established. Dye tracers do not require a hydrologic continuum, laminar flow, or any other theoretical construct in order to be applied successfully in hydrogeologic investigations.

Single-Well Tests

A single-well tracer test (sometimes called borehole dilution) can be used to estimate the average horizontal ground-water-flow velocity in the vicinity of a well. The test is conducted by introducing a tracer into a section of a well that has been isolated by use of packers. The tracer is continuously mixed so its concentration is kept uniform throughout the isolated interval. The continuous lateral flow of ground water through the interval dilutes the tracer. Measurements of tracer dilution through time can be analyzed (Freeze and Cherry, 1979, p. 428; Drost and others, 1968) to estimate the average horizontal velocity of ground water near the well.

A single-well pulse tracer test can be conducted by placing a tracer in a well and recovering it at some later time (Davis and others, 1985; Leap and Kaplan, 1988). By analyzing the breakthrough curve for recovered tracer, the travel distance of tracer under a natural gradient can be estimated.

Multiple-Well Tests

Tracer tests can be conducted by use of two or more wells under natural or radial-flow conditions. In fractured-rock aquifers, natural flow tests are difficult to conduct because likely ground-water-travel paths are difficult to evaluate a priori. Because travel paths are usually unknown, a tracer might never be recovered at any observation well during a natural-flow test. Pumping a well to induce radial flow greatly increases the chances for successful tracer recovery. This type of test can be conducted in several configurations: (1) Recirculating test—a tracer is continuously injected at one well and recovered by pumping at another well (Grove and Beetem, 1971); (2) Radially converging test—a tracer pulse is injected at one well and is removed by continuously pumping a nearby well (Davis and others, 1985); and (3) Radially diverging test—the tracer is continuously injected at one well while its recovery is monitored by sensors in nearby observation wells (Davis and others, 1985).

Example for a Hypothetical Aquifer

The stepwise refinement of the conceptual model of ground-water flow and area of contribution to a supply well for a hypothetical aquifer is discussed here and illustrated in figure 7. The hypothetical well is completed in siliciclastic rocks in the Piedmont Physiographic Province. The surrounding land use is agricultural except for light industry on the sandstone ridge. The well is 800 feet deep and withdraws water at an average rate of 230 gallons per minute.

The contributing area for this well was delineated by refining the conceptual model of sources of water to the well in two steps. Hydrogeologic information used to refine the conceptual model was from 11 hydrogeologic tests shown in table 5: (1A) topographic mapping, (1B) geologic mapping, (1C) fracture delineation, (1D) water-table configuration, (2B) streamflow measurements, (3A) chemical differences of water sources, (4B) borehole logging, (4C) borehole flowmetering, (5B) constant-discharge aquifer tests, (5C) step-discharge aquifer tests, and (6B) multiple-well tracer tests. The information that was collected and analyzed in successive steps ranged from simple to complex; more complex methods to delineate a contributing area were used as more complex data were incorporated.

Step 1.—The initial conceptual model for this hypothetical aquifer is based on very scanty information. No data are available on hydrologic properties, the hydrologic framework is assumed to be simple, and the streams are assumed to act as fully penetrating (fig. 7a). Initially, the watershed in which the well is situated is identified (fig. 7b, area 1A). This is a large area (about 8 square miles) that probably does not entirely contribute water to the well; however, it provides a first approximation of the contributing area. A more reasonably sized contributing area is approximated by use of a water budget. Base-flow runoff measured at the streamflow-gaging station was 12 inches per year. Assuming that recharge equals base-flow runoff, the surface area through which the recharge rate will equal the pumping rate of 230 gallons per minute is about 0.6 square mile. The exact location of this area is unknown, so it is sketched as a circular area around the well (fig. 7b, area 2B). The position of this area, however, needs adjustment because it doesn't fit with the conceptual model (fig. 7a). A map from a published report and from measurements of ground-water levels in the vicinity of the supply well indicates the water-table gradient is about 40 feet per mile to the northeast. The 0.6 square-mile area is then adjusted by use of the uniform-flow equation (table 4) and a textbook value for hydraulic conductivity, so that the contributing

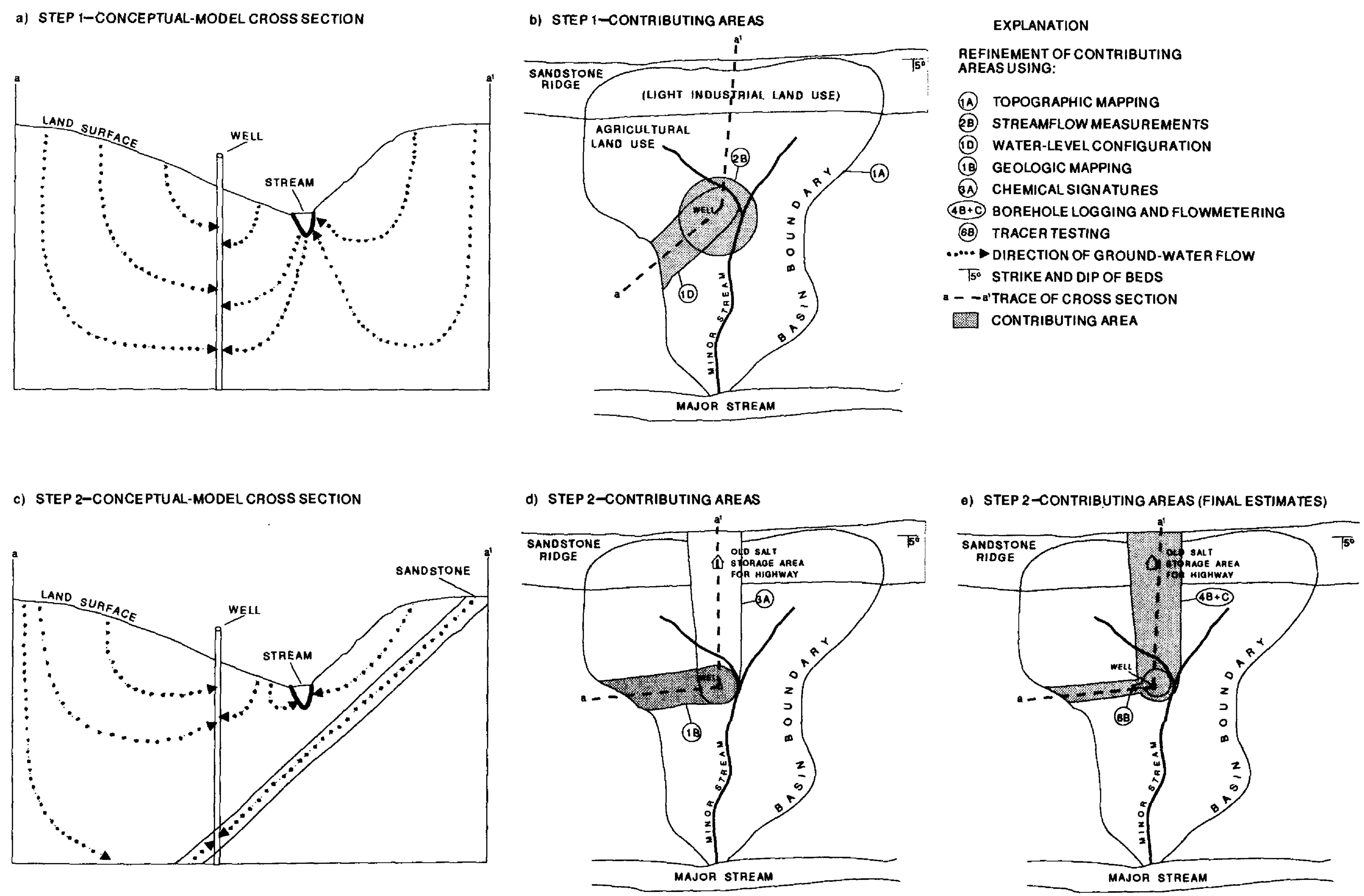

Figure 7. Example of stepwise refinement of contributing area. (Analysis steps are defined in table 5.)

area is oriented in the direction of the water-level gradient and that it extends to the watershed divide (fig. 7b, area 1D). This completes step 1. It is assumed that the system is simple and acts on a homogeneous hydrologic continuum with simple boundaries.

Step 2.—In the next step of refinement, geologic mapping and borehole geophysics are employed to refine the hydrologic framework, an aquifer test is conducted to estimate hydraulic properties, and chemical signatures and a tracer test help directly identify the water source. This information leads to a more complex conceptual model (fig. 7c) and the delineations shown in figure 7d and 7e. In step 1, although a contributing area was delineated, adjustments for hydrologic discontinuities caused by geologic structures and fractures were not made. Step 2 begins with an analysis of geologic structure and fracture traces. The geologic structure indicates that the rocks strike east-west and dip to the south at about 5 degrees. Exposed surficial rocks are siltstone except for a sandstone ridge that crops out in the northern part of the basin. The strike of the rocks indicates the aquifer may be anisotropic, and the preferred pathway of ground-water flow may be east-west. The anisotropy probably skews the contributing area shape, but the effect is unknown. The orientation of contributing area 1D is shifted to a more east-west alignment to account for the inferred anisotropy (fig. 7d, area 1B). The geologic information also indicates the sandstone unit could be encountered by the well at a depth of about 600 feet, which could provide ground water through a deep confined system (fig. 7c).

Water samples collected from the supply well contained elevated concentrations of nitrate, pesticides, and sodium chloride. The presence of nitrate and pesticides indicates that some water probably recharges the aquifer through agricultural lands surrounding the well. The source of the salt is unknown, but it may originate from the road-salt storage on the sandstone ridge. A tentative additional contributing area is sketched that encompasses the possible road-salt source (fig. 7d, area 3A).

Borehole-geophysical methods were used to identify water-bearing fractures in the supply well. Major fracture zones were identified at depths of 640 to 680 feet and 50 to 90 feet. The deep fractures are in the sandstone unit that crops out along the northern boundary of the basin. Borehole flowmetering during pumping indicates that each fracture zone provides about half of the water withdrawn from the well. These data are incorporated into a numerical model and the resultant contributing area is shown to be complex; one part originates on the outcrop area on the sandstone, which provides recharge to the deep fractures, and one part provides water through shallow fractures (fig. 7c, areas 4B+C).

An aquifer test was conducted by pumping the supply well in five steps of 100 gallons per minute at rates of 100 to 500 gallons per minute. When pumped at 400 gallons per minute, the water level in the well dropped below the base of the upper fracture zone, which resulted in a rapid decline of water level in the well. This verifies the upper fracture was supplying a large proportion of water to the well. A constant-discharge aquifer test was conducted by use of observation wells completed at depths less than 200 feet. After 12 hours of pumping, the drawdown extended in an east-west direction, which supports the inference of strong anisotropy in the shallow aquifer. The drawdown distribution indicates the effects of anisotropy are probably greater than the previous model simulation showed. The anisotropy data are incorporated into the numerical model to refine the delineation shown in figure 7d (area 4B+C). Because deep observation wells are not available, the anisotropy of the deeper aquifer is unknown.

Finally, observation wells were drilled into the deep and shallow aquifers and tracers were introduced in nearby wells to delineate a time-of-travel area. These results verify the general directions of ground-water flow in the shallow and deep water-bearing zones. A 30-day time-of-travel area is sketched (fig. 7d, area 6B). The time involved to verify longer travel paths is significantly greater.

Although the hypothetical example discussed here is simplistic, it illustrates stepwise analysis by use of refinement of conceptual models. In general, the better the understanding of the hydrologic system, the more accurate the delineation of the contributing area will be, regardless of the method used.

SUMMARY

Ground water provides a drinking-water supply for more than 2 million Pennsylvanians. About three fourths of these ground-water supplies are derived from bedrock aquifers. These aquifers can be grouped into three categories: siliciclastic, carbonate, and crystalline.

Because sources of potential contamination to community-supply wells are widespread in Pennsylvania, it is important to identify the area contributing water to a supply well so activities that might degrade the quality of that source can be minimized or eliminated. Unfortunately, delineating a contributing area to a well completed in a fractured-bedrock aquifer in Pennsylvania is difficult, because ground-water flow is usually through a heterogeneous network of secondary openings that are not easily characterized or simulated at the well-field scale. Therefore, a strategy for refining the understanding of boundary conditions and major heterogeneities that control ground-water flow and sources of water to a supply well is recommended.

The strategy is based on the development and stepwise refinement of a conceptual model of ground-water flow to the supply well or spring. Hydrogeologic information from one or more of these categories—(1) hydrogeologic mapping, (2) water-level and streamflow measurements, (3) geochemical sampling, (4) geophysical surveys and borehole flowmetering, (5) aquifer testing, and (6) tracer testing—will be needed to refine the conceptual model. The hydrologic information is logically collected by phasing the investigation, initially by collection and analysis of the data that are easy to acquire, then conducting more complex methods to refine the conceptual model and contributing-area delineations.

Using such a strategy, the improved understanding of the ground-water-flow system will lead to a technically defensible delineation of the contributing area, provided the delineation method incorporates the important features of the conceptual model. Numerical modeling applied to explicitly incorporate major heterogeneities with zones of differing hydraulic properties is one versatile method to capture the main features of the ground-water-flow system where a few fractures provide preferential flow pathways. However, all delineations, especially for time-of-travel areas, should be considered estimates on the basis of available information, which can be verified only by the recovery of a tracer injected from a known source.

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GLOSSARY

Aquifer.—A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs (Lohman and others, 1972, p. 2).

Anisotropy.—The condition of having different properties in different directions. Properties that are dependent upon direction are said to be anisotropic.

Area of diversion.—Surface area of the aquifer that has the same horizontal extent as the volume throughout which water is diverted to the well (Brown, 1963).

Area of influence.—The area throughout which water levels decline measurably because of discharge from a well. Theoretically, the effects of pumping extend to the boundary of the aquifer.

Capture zone.—See zone of diversion.

Continuum.—A continuous extent of aquifer where ground water moves through numerous pathways so that its average flux is independent of sampling scale.

Contributing area.—Area of diversion along with any adjacent surface areas that provide recharge to the aquifer within the zone of diversion.

Homogeneity.—A material is homogeneous if its hydrologic properties are identical everywhere. Synonymous with uniformity. (Lohman and others, 1972, p. 8.)

Hydraulic conductivity.—The hydraulic conductivity of the medium is the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow (Lohman and others, 1972, p. 4).

Induced infiltration.—Seepage to an aquifer from a naturally gaining surface-water source induced by a reversal of the hydraulic gradient due to pumping.

Isotropy.—The condition in which all significant aquifer properties are independent of direction (Lohman and others, 1972, p. 9).

Specific capacity.—The rate of discharge of water from the well divided by drawdown of water level within the well. Specific capacity decreases with duration of pumping. (Lohman and others, 1972, p. 11.)

Specific yield.—The ratio of volume of water yielded from water-bearing material by gravity drainage, as occurs when the water table declines, to the volume of the water-bearing material.

Storage coefficient.—The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head (Lohman and others, 1972, p. 13).

Streamflow depletion.—The reduction of streamflow caused by pumping due to either induced infiltration or the capture of ground water that would have reached the stream if the pumping had not diverted it to the well.

Transmissivity.—The rate at which water at the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient (Lohman and others, 1972).

Wellhead-protection zone.—The surface and subsurface area surrounding a water well or well field, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or wellfield (U.S. Environmental Protection Agency, 1987).

Zone of diversion.—The aquifer volume through which water is diverted to the well.