Delineating Groundwater Sources and Protection Zones

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This booklet is part of a series of educational brochures and slide sets that focuses on various aspects of water source protection. The series has been prepared jointly by the University of California Agricultural Extension Service and the California Department of Health Services.

For further information about this and other documents in the series, contact the project team leader (see below) or visit the following website:

www.dhs.ca.gov/ps/ddwem/dwsap/DWSAPindex.htm

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Cover illustration: Groundwater protection zones for five city-owned water supply wells in Sebastopol, Calif. Zones were delineated by applying the Modified Calculated Fixed Radius (Modified CFR) method. Innermost circles represent Zone A. Larger, composite circles (intermediate areas enclosed by solid lines) represent Zones B5 and B10. Outermost envelopes (dashed lines) represent optional Buffer Zones 20 and 50. Excerpted from City of Sebastopol Demonstration Project report by Leah G. Walker, California Dept. of Health Services, Division of Drinking Water and Environmental Management, Santa Rosa, Calif. (November 1998).

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The portion of land that contributes water to a particular well by seepage or other means is called the *well recharge area* (Figure 1). Delineating a water well's recharge area is the first step in the water source protection process outlined by the California Drinking Water Source Assessment and Protection (DWSAP) Program (California Department of Health Services, 1999).

This booklet provides an overview of the methods available for delineating the recharge area of a groundwater well. It begins by introducing several simple, easy-to-learn geometric and analytical methods that can serve as preliminary delineation tools. It then outlines briefly the more elaborate approaches typically implemented by professional hydrogeologists: hydrogeologic mapping and computer modeling.

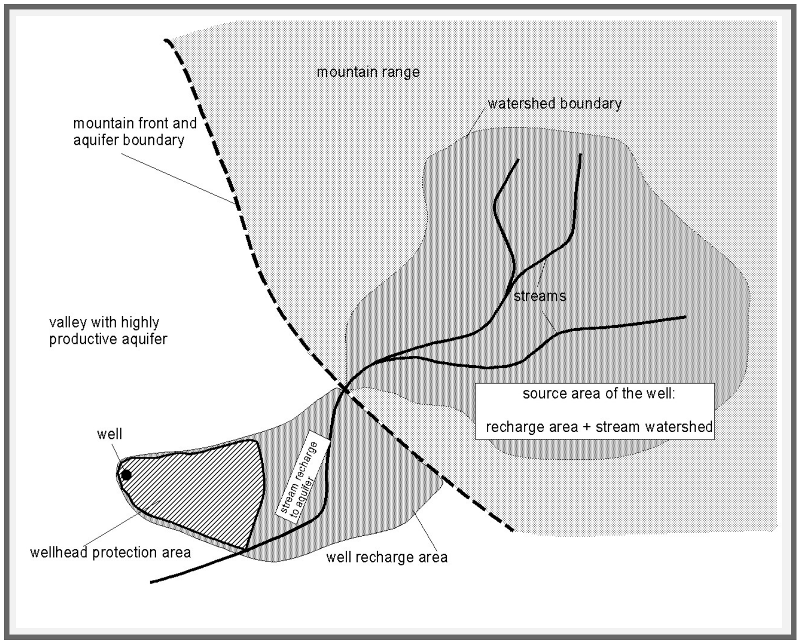

Figure 1: Conceptual illustration showing the relationship of wellhead protection area, recharge area, and source area of a well.

Source Areas and Protection Zones

Knowing a well's recharge area alone may not suffice to protect water in the well. For example, if significant recharge occurs from lakes and rivers, the watersheds upstream from those lakes and rivers should be considered in a protection plan, too. The DWSAP program therefore uses the term *source area* rather than recharge area. The source area is at least as large as the (estimated) recharge area. It may be much larger than the recharge area if upstream watersheds have a significant effect on the water quality of rivers and streams that recharge the aquifer (Figure 1).

The federal Safe Drinking Water Act defines a *wellhead protection area* within the recharge area of a well 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 a water well or well field." The wellhead protection area can be identical to the well's recharge area, or smaller than the recharge area. The wellhead protection area is sometimes intentionally chosen to be smaller than the recharge area, because not all contamination introduced in the source area of a well will necessarily reach the well. Natural processes such as chemical transformation, biological degradation, or adsorption onto aquifer materials may reduce the concentrations of contaminants to acceptable levels before the water reaches the well. In addition, many bacteria and viruses have a limited life span; such organisms may therefore travel only short distances toward a well before they are inactivated. Figure 1 illustrates the relationship between wellhead protection area (also called *protection zone* in DWSAP), recharge area, and source area of a drinking water well.

For purposes of assessment and protection planning, three major goals can be identified:

- The well must be protected from direct contamination in the immediate vicinity of the well.
- The well water must be protected from microbial contamination.
- The well water must be protected from chemical contamination.

Each of these goals is associated with a different protection area. The first goal typically requires a relatively small protection area. The third goal (protection against chemical contamination) often requires a relatively large protection area.

The farther away from a well a potentially contaminating activity (PCA) takes place, the more opportunity there may be for inactivation of the contaminant (also referred to as natural attenuation).Even for persistent contaminants that are not subject to attenuation, more distance means more time until contamination reaches the well. That gives time to manage a contamination problem. Each of the above protection goals may require a different set of assessment and protection measures. It is therefore useful to subdivide the source area into several zones based on whether the impact of a PCA results in a high, medium, or low risk of well contamination and whether the impact is immediate, short-term, or long-term. Each such zone would require a different level of protection and management measures.

Several criteria can be used to delineate the wellhead protection area (WHPA) or the protection zones within the source area. These have been outlined in the original EPA guidance document on delineation of WHPAs (EPA, 1987):

- *Distance*: Specify an arbitrary distance based on past experience, regardless of hydrogeologic conditions.
- *Drawdown*: Specify the cone of depression created as a result of well pumping (also called "zone of influence") as the protection zone. (Note, however, that in most California aquifers the cone of depression and the recharge area only partially overlap with each other.)
- *Time of travel (TOT)*: Utilize the time of contaminant travel to the well to delineate protection zones.
- *Flow boundaries*: Utilize obvious hydrogeologic and geomorphic features (water divide, watershed boundaries, hydrogeologic boundaries) to delineate the protection zone (also called "zone of contribution").
- *Assimilative capacity*: Most soils and most groundwater aquifers have a natural capacity to reduce the concentrations of dangerous microbes and chemicals. Therefore, a protection zone sometimes can be designed to assure that the protection zone itself provides enough aquifer capacity to assimilate or attenuate specific contaminants entering the aquifer from outside the zone. A zone designated by this criterion is sometimes referred to as the "zone of attenuation."

The risk of a contaminant reaching the well without being detected or mitigated prior to arrival depends primarily on its time of travel. The time of travel of a contaminant from its source to the well increases, of course, with travel distance to the well. But time of travel is not only a function of distance, it is also dependent on the type of geologic material present, the thickness and extent of the aquifer (or multiple aquifers), the depth of the water table, the thickness of the aquifer, and whether the aquifer in question is unconfined, partially confined (semi-confined), or confined. (For definitions of the latter terms, consult the accompanying booklets on hydrogeology and contaminant transport.)

In California, different protection zones serve different purposes. For the immediate vicinity of the wellhead, DWSAP defines a Well Site Control Zone: a circular area with minimum radius of 50 feet. DWSAP also defines a Zone A, a Zone B5, a Zone B10, and a Buffer Zone. Zone A, which is intended to protect against microbial and direct chemical contamination, encompasses all area for which the contaminant travel time is two years or less. Zone B5, intended to protect against chemical contamination, encircles or encompasses the area for which contaminant travel time is five years or less. Zone B10, also for protection against chemical contamination, encompasses the area for which travel time is 10 years or less. (For more details, see DWSAP guidance document, section 6.2.5.)

DWSAP has chosen distance, time of travel (TOT), and flow boundaries as the main criteria for delineation of the various zones. For a well site control zone, the main criterion is distance. For zones A, B5, and B10, the criterion is time of travel. The buffer zone and the well recharge area or source area are delineated by flow boundaries.

Zone A is defined based on the general recognition that most microbiological contaminants become ineffective after being submerged in groundwater for more than two years. Chemical contaminants, on the other hand, can travel over long distances for many years. Just one example is the widespread DBCP pesticide contamination found in California groundwaters now, more than 20 years after the chemical was last used by farmers. The further away from a well such contamination occurs, the more time (and space) there is for site assessment and remedial action (e.g., soil cleanup, pumping and treating of groundwater, installation of filters, etc.). Hence, the definitions for B5, the intermediate (5 year) time-of-travel zone, and B10, the long-term (10 year) time-of-travel zone.

Classification of Delineation Methods

Methods for delineating recharge areas and the various protection zones range from very simple to very complex. In this booklet, we distinguish four major groups of delineation methods. The four groups are listed below by increasing complexity:

1. *Geometric or graphical methods* involve the use of a pre-determined fixed radius and aquifer geometry without any special consideration of the flow system, or they involve the use of simplified shapes that have been pre-calculated for a range of pumping and aquifer conditions.
2. *Analytical methods* allow calculation of distances for protection zones using equations that can be solved on a hand calculator or in a microcomputer spreadsheet program. Analytical methods are available both for time-of-travel calculations and for drawdown calculations.
3. *Hydrogeologic mapping* involves identifying the recharge zone and the source zone based on geomorphic, geologic, hydrologic, and

hydrochemical characteristics of an aquifer. This method is used in combination with simple analytical methods. In addition, it is often a necessary first step when using more complex analytical methods or when constructing a numerical computer flow-and-transport model.

4. *Computer modeling methods* involve devising, calibrating, and applying complex analytical or numerical models that simulate groundwater flow and contaminant transport processes. These methods can be broadly grouped into simple and complex models.

The above classification scheme is similar to that used in U.S. EPA (1987), except that:

1. The arbitrary fixed radius, volumetric flow equation, and simplified shapes methods are all placed in the geometric category.
2. Calculated fixed radius is excluded as a category because the two examples given in the EPA document fall into separate categories (the volumetric equation method is geometric, and the Vermont Department of Water Resources method is a simple analytical method using a drawdown criterion).
3. The numerical flow-and-transport models category includes more complex analytical models that require computer programs for solution.

A brief description of the simple graphical methods that meet the minimum requirements set by DWSAP for delineating the recharge area, the source area, and the various zones within the source area can be found in section 6.2 of the DWSAP guidance document. The following pages provide an overview of all four types of methods; this overview is essentially an edited version of Chapters 4 and 5 in the *Handbook on Ground Water and Wellhead Protection* (U.S. EPA, 1994).

Selecting a Method

Table 1 summarizes the advantages and disadvantages of three geometric methods and three other major types of methods for delineating wellhead protection areas (WHPAs) or protection zones. The various methods require different levels of expertise and work time, as shown in Table 2. The amount of time needed per well for delineation depends primarily on the amount of data already available and the format in which the data are available.

Drinking-water wells in California occur in many different hydrogeologic zones. Different methods may be more accurate in some types of aquifers than in other types of aquifers. Therefore, California's DWSAP program does not prescribe a particular delineation method. The only requirement is that zones must be delineated based on the time-of-travel criterion.

The choice of method for completing a delineation will depend on a number of technical, policy, and financial criteria:

- Availability of data and regional or local hydrogeologic knowledge
- Hydrogeologic setting
- Accuracy desired
- Financial resources available
- Defensibility against potential challenges and litigation
- Relevance to the protection goal

Generally, the less data available, the simpler the initial delineation method will have to be. If the lack of basic hydrogeologic data severely limits the choice of delineation method, it may be of long-term financial advantage to initiate a data collection program that can generate the necessary knowledge for a more accurate delineation of the protection zones using more complex tools. Inaccurate estimation of the protection zone may lead either to a lack of appropriate protection for the drinking water well (underdesign) or to an unnecessarily large investment in maintaining a grossly overdesigned protection area. These future costs should be considered when deciding which method may be the most economic one to apply. Some examples are given in the sections that follow.

Geometric Methods

Geometric methods for wellhead delineation either require no mathematical calculations at all (e.g., arbitrary fixed radius method or simplified variable shapes method) or they require simple volumetric calculations based on pumping rate and aquifer porosity (e.g., cylinder method). The distinction between these methods and "analytical methods" (described later) is somewhat arbitrary: although predefined shapes can be used without much knowledge of the aquifer, someone must calculate ahead of time the size or shape—and that requires either an analytical method or complex computer modeling.

It is important to understand that the use of predefined shapes or geometries works only if the hydrogeologic setting and pumping rate for which these were developed are similar to the well site to which the method is applied.

Arbitrary Fixed Radius

The arbitrary fixed radius method (Figure 2) requires only (1) a base map, (2) a defined distance criterion based on a generalized application of time-of-travel or

Table 1: Methods for Delineating Wellhead Protection Areas

GEOMETRIC METHODS

Method	Advantages	Disadvantages
Arbitrary Fixed Radius (distance)	▪ Easily implemented ▪ Inexpensive ▪ Requires minimal technical expertise	▪ Low hydrogeologic precision ▪ Large threshold radius required to compensate for uncertainty will generally result in overprotection ▪ Highly vulnerable aquifers may be underprotected ▪ Highly susceptible to legal challenge
Cylinder Method (calculated fixed radius)	▪ Easy to use ▪ Relatively inexpensive ▪ Requires limited technical expertise ▪ Based on simple hydrogeologic principles ▪ Only aquifer parameter required is porosity ▪ Less susceptible to legal challenge	▪ Tends to overprotect downgradient and underprotect upgradient because does not account for ZOC ▪ Inaccurate in heterogeneous and anisotropic aquifers ▪ Not appropriate for sloping potentiometric surface or unconfined aquifer
Simplified Variable Shapes (TOT, flow boundaries)	▪ Easily implemented once shapes of standardized forms are calculated ▪ Limited fluid data required once standardized forms are developed (pumping rate, aquifer material type, and direction of ground water flow) ▪ Relatively little technical expertise required for actual delineation ▪ 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 ▪ Inaccurate in heterogeneous and anisotropic aquifers

OTHER METHODS

Method	Advantages	Disadvantages
Simple Analytical Methods (TOT, drawdown, flow boundaries)	▪ More accurate than simplified variable shapes because based on site-specific parameters ▪ Technical expertise required, but equations are generally easily understood by most hydrogeologists and civil engineers ▪ Various equations have been developed, allowing selection of solution that fits local conditions ▪ Allows accurate characterization of drawdown in the area closest to a pumping well	▪ Relatively extensive data on aquifer parameters required for input to analytical equations ▪ Most analytical models do not take hydrologic boundaries, aquifer heterogeneities, and local recharge effects into account
Hyrogeologic Mapping (flow boundaries)	▪ Well suited for unconfined aquifers in unconsolidated formations and to highy anisotropic aquifers, such as fracture bedrock and conduit-flow karst ▪ Necessary to define aquifer boundary conditions	▪ Less suitable for deep, confined aquifers ▪ Requires special expertise in geomorphic and geologic mapping and judgement in hydrogeologic interpretations ▪ Moderate to high manpower and data-collection costs
Computer Semi-Analytical and Numerical Flow Transport Models (TOT, drawdown, flow boundaries)	▪ Most acccurate of all methods and can be used for most complex hydrogeologic settings, except where karst conduit flow dominates ▪ Allows assessment of natural and human-related effects on the ground water system for evaluating management options	▪ High degree of hydrogeologic and modeling expertise required ▪ Less suitable than analytical methods for assessing drawdowns close to pumping wells ▪ Extensive aquifer-specific data required ▪ Most expensive method in terms of manpower and costs of data collection and analysis.

from EPA, 1994

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. Refer to Table 1 for advantages and disadvantages of this method.

Table 2: Estimated Work Hours, Expertise, & Overhead Costs for Delineation [1]

METHOD	WORK HOURS	LEVEL OF EXPERTISE [2]	OVERHEAD COSTS
Geometric Methods	1 to 10	1, 2	low
Analytic Methods	2 to 20	3	moderate
Hydrogeologic mapping	4 to 40	3	moderate to high
Computer modeling	10 to 200	4	high

[1] *After E.P.A., 1987*

[2] *Key to levels of expertise: 1 = non-technical; 2 = junior hydrogeologist; 3 = mid-level hydrogeologist/modeler; 4 = senior hydrogeologist/modeler*

Under California's DWSAP program, this method can only be used for non-community water systems. It is the simplest method, but also the least accurate method. To provide a conservative measure of protection, the protection area typically ends up being relatively large. In most applications, an arbitrary fixed radius is chosen based on transmissivity and pumping rate, thereby indirectly accounting for time of travel. Table 3 identifies fixed radii for a number of different aquifer types (in Idaho), where the radius is based on pumping rate and transmissivity and depends on the time of travel required. The method allows identification of an interim protective radius until more accurate wellhead delineation methods can be used.

Calculated Fixed Radius (Cylinder Method)

The calculated fixed radius method (CFR) uses a volumetric flow equation to calculate a fixed radius around a well from which water will flow at a specified time of travel (Figure 3). Because it involves solving a simple equation, it is also an example of a very simple analytical method. In the CFR method, the radius, in effect, defines a circular time-of-travel isochrone around the well. The circle delimits a cylinder within the aquifer that holds exactly the amount of water that is pumped during the specified period. In other words, what comes out of the well must be equal to what was in the aquifer cylinder before (principle of water mass balance). Applying the principle of water mass balance, the equation for calculating the fixed (cylinder) radius, from which water comes within some time of travel, *t*, is:

$$r_t = \mathrm{Sqrt}\,[\ Q\,t\ /\ \pi\, n\, b\ ] \qquad (1)$$

where:

Q = pumping capacity of well, in ft^3/year (note: ft^3/year = gpm · 70,257)

t = time of travel, in years (2, 5, or 10 years for Zones A, B5, and B10, respectively)

$\pi = 3.1416$

n = aquifer porosity, usually from 0.1 to 0.3 (10%–30%); where unknown, the California DWSAP specifies to use 20%

b = open interval or length of well screen, in feet; where unknown, the California DWSAP specifies that b (in feet) is equal to 0.1 times the maximum pumping rate (in gpm)

r_t = radius of zone, in feet, for time of travel t

The CFR method ignores the complexity of groundwater flow. Equation 1 is therefore only a coarse approximation. It is most appropriate for a confined aquifer with little vertical leakage from the overlying confining bed. It can also be used in unconfined aquifers, if:

- the depth of the cone of depression generated

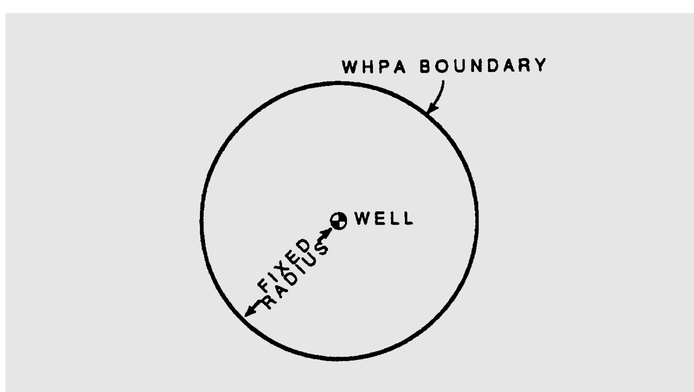

Figure 2: Delineation of wellhead protection area by fixed radius method. (From EPA, 1994, Figure 4-4)

Table 3: Calculated Fixed Radii for Major Aquifers in Idaho [1]

Pump Rate	50 gpm[2]	100 gpm	500 gpm	1000 gpm	2000 gpm	5000 gpm	7000 gpm
EAST SNAKE RIVER PLAIN BASALTS							
2-year TOT[3]	1800	1800	2000	2300	2700	3900	4600
5-year TOT	4400	4400	4700	5000	5600	6900	7700
COLUMBIA RIVER BASALTS							
Pump Rate	50 gpm	100 gpm	500 gpm	1000 gpm	2000 gpm	5000 gpm	7000 gpm
2-year TOT	300	400	900	1300	2200	4500	6000
5-year TOT	400	800	1300	2000	2900	5400	7000
UNCONSOLIDATED ALLUVIUM							
Pump Rate	50 gpm	100 gpm	500 gpm	1000 gpm	2000 gpm	5000 gpm	7000 gpm
2-year TOT	6500	6600	7100	7700	8600	12000	14000
5-year TOT	16000	16000	17000	18000	19000	22000	24000
MIXED VOLCANIC & SEDIMENTARY ROCKS							
Pump Rate	50 gpm	100 gpm	500 gpm	1000 gpm	2000 gpm	5000 gpm	7000 gpm
2-year TOT	3200	3300	3400	3600	3900	4800	5400
5-year TOT	8200	8200	8400	8600	9000	10000	11000
MIXED VOLCANIC & SEDIMENTARY ROCKS (PRIMARILY SEDIMENTARY ROCKS)							
Pump Rate	50 gpm	100 gpm	500 gpm	1000 gpm	2000 gpm	5000 gpm	7000 gpm
2-year TOT	200	200	400	600	900	1600	2000
5-year TOT	300	400	700	1000	1300	2200	2700

1 *After EPA, 1994*
2 *gpm = gallons per minute*
3 *TOT = time of travel*

by the well is less than one-tenth of the aquifer thickness, and

- the regional recharge rate to the unconfined aquifer is negligible.

In both cases (confined and unconfined aquifer), the method only produces a realistic protection zone if the regional groundwater gradient is very flat (<0.0005 or 0.001).Steeper gradients will result in a zone of influence that is not circular (see below, under Analytical Methods).

Calculated Fixed Radius in Leaky Aquifers or Unconfined Aquifers with Significant Regional Recharge

In partially confined (leaky) aquifers or in unconfined aquifers with significant regional recharge, the volumetric flow equation results in overprotection, because it does not account for flow into the aquifer from vertical leakage through the confining bed, which is also captured by the well. If the vertical leakage rate of water, q_l (feet/day), can be reasonably well quantified by analyzing pumping test data or by using Darcy's Law, then the vertical contribution to well pumpage, Q_l, within the zone r_t is equal to:

$$Q_l = q_l \pi r_t^2$$

The total pumpage is therefore the sum of the leakage to the aquifer within r_t and the aquifer volume itself to be pumped within r_t:

$$Q = Q_a + Q_l \qquad (2a)$$

Under leaking conditions, we obtain from mass balance considerations that:

$$r_t = \mathrm{Sqrt}\left[\, Q\, t \,/\, \pi\, (n\, b + t\, I\,)\,\right] \qquad (2b)$$

where:

I = net annual recharge rate, in feet per year

and r_t, Q, t, n, and b are as specified previously

The solution to Equations 2a and 2b is programmed into worksheet "CFR method" in "delineation.xls" (see accompanying CD-ROM disk). There, leakage from an underlying and overlying aquifer can also be considered. If this method is applied to an unconfined aquifer that meets the two requirements listed in the previous section, then the net annual recharge rate I (feet/year) replaces the leakage rate q_l in Equation 2a.

In California, the net recharge rate, I, from the root zone to the groundwater table ranges from less than 0.01 ft/yr to 0.1 ft/year in non-irrigated areas of the southeastern desert region, the southern coastal areas,

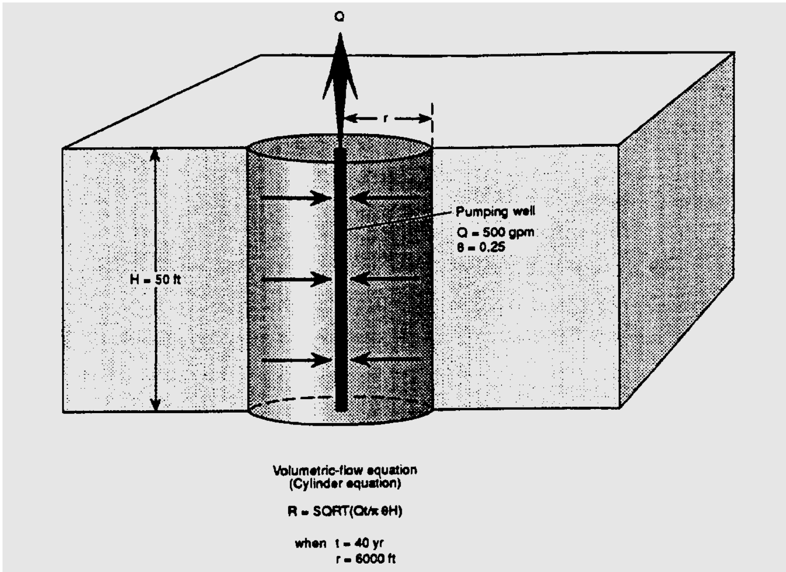

Figure 3: Delineation of wellhead protection area by cylinder method. (From EPA, 1994, Figure 4-4)

and the Central Valley. In mountainous areas of Northern and Central California, recharge rates may be as high as 1 ft/year. In areas with a large percentage of irrigated agriculture, the percolation of surplus irrigation water is the main source of recharge water; recharge in such areas ranges from 0.25 ft/yr to 1.5 ft/yr, depending on the efficiency of the irrigation methods used.

Computing Leakage Rate in a Leaky Confined Aquifer

Leakage into a production aquifer (the aquifer from which a particular well draws water) from an overlying or underlying aquifer is a common situation. The following example illustrates how to compute the leakage rate in such a situation.

Example: Two or more aquifers are separated by a more or less well defined aquitard, through which flow is primarily vertical. Determining leakage rate, q_l (in feet/year), from one aquifer to another via a confining aquitard unit can be achieved by using the principle of Darcy's Law:

$$q_l = Q_l / A = 48.79\ K_v\ i$$

where:

$$i = (h_{outside} - h_{production}) / b_1$$

q_l = quantity of leakage, in feet per year

Q_l = total leakage, in ft^3/year

A = cross-sectional area through which leakage occurs, in ft^2

K_v = vertical hydraulic conductivity of the confining unit, in gpd/ft^2 (1 gpd/ft^2 = 48.79 ft/year)

i = hydraulic gradient across the confining unit

b_1 = thickness of the confining unit, in feet

$h_{outside}$ = average head (water level) in the overlying or underlying aquifer (above or below the production aquifer), in feet

$h_{production}$ = average head (water level) in the production aquifer, in feet

Figure 4 illustrates two aquifers separated by a layer of clayey silt. The clayey-silty confining unit is 10 feet thick and has a hydraulic conductivity of 0.1 gpd/ft^2. The difference in water level between wells tapping the upper and lower aquifers is 15 feet. The leakage rate is:

q_l = 48.79 [ft^3/gal · day/year] · 0.1 gpd/ft^2 · 15 ft / 10 ft = 7.33 ft/year

Assuming that, for example, protection zone A turns out to have an area of 1 square mile (27.8784 million square feet), the annual quantity leaking from the deeper aquifer to the shallower one is:

Q_l = 7.33 ft/year · $(5280\ ft)^2$ =204 million cubic feet per year (= 2,900 gpm)

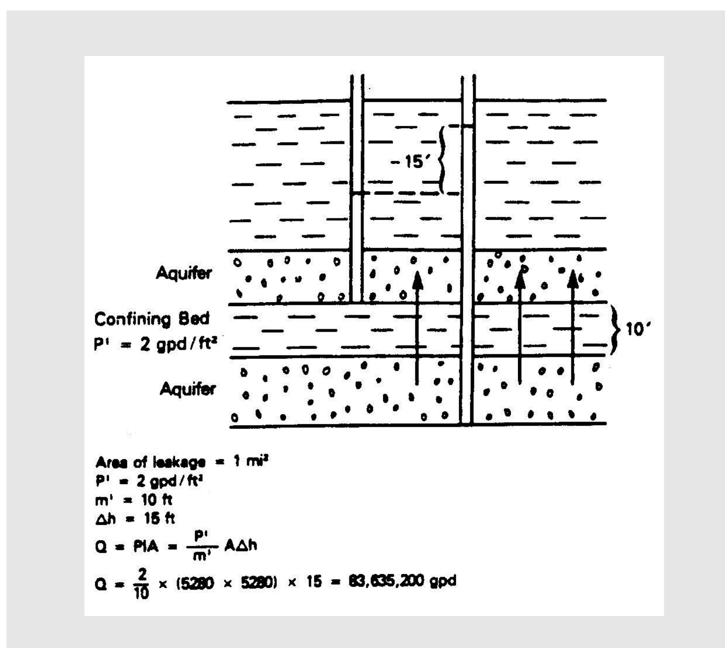

Figure 4: Using Darcy's law to calculate the quantity of leakage from one aquifer to another. (From EPA, 1994, Figure 4-9)

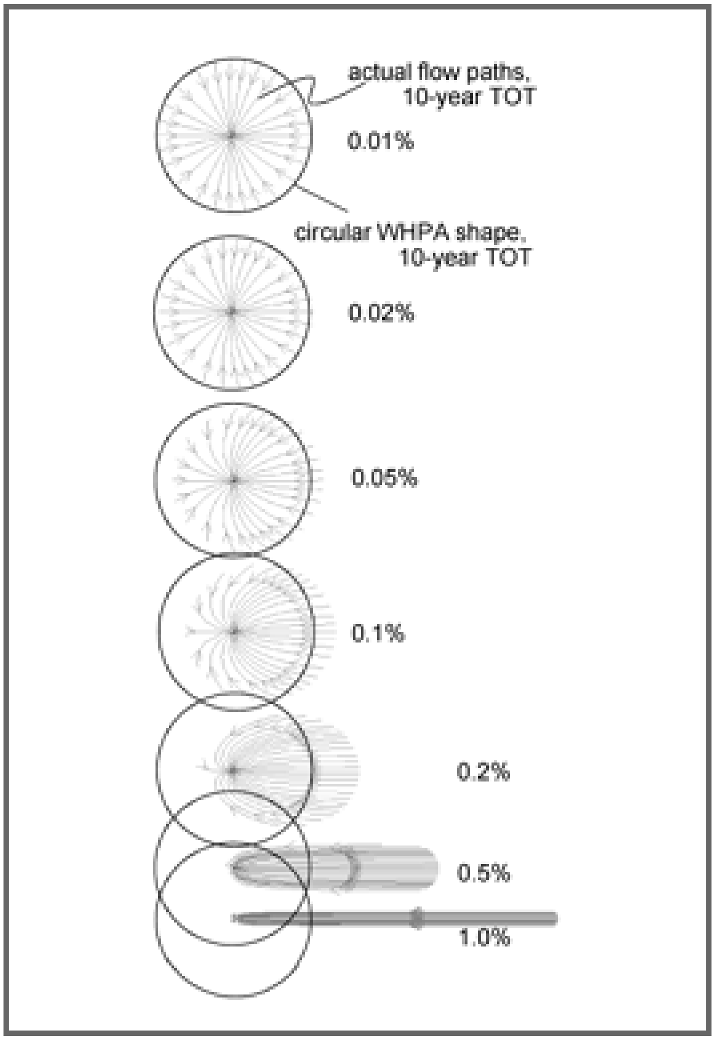

Figure 5: Groundwater flow paths to a pumping well with a capacity of 1,000 gpm in a 100 ft. thick aquifer with a hydraulic conductivity of 748 gpd/ft^2 (100 ft/day). Regional groundwater flow is from right to left. The ten-year time-of-travel (TOT) zone is demarcated by the outer beginning of the flow paths. The tips of the arrows along the flow paths demarcate the five-year TOT zone. This figure illustrates the influence of the regional hydraulic gradient on the shape of the five- and ten-year TOT and compares it to the equivalent shape obtained from the calculated fixed radius (CFR) method for the 10-year TOT (circle). At very small slopes (< 0.05%), the shape of the two TOT zones is approximately circular. The greater the regional slope of the aquifer, the less circular the shape. Clearly, at slopes of 0.1% or larger, the cylinder method (circular protection area) yields a poor estimate of the actual wellhead protection area.

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

Some authors have proposed using the time of travel across a confining layer as one of several criteria for differentiating semiconfined aquifers from highly confined aquifers.Vertical time of travel across a confining layer is:

$$t_v = h_1 \, q_l \, / \, b_1$$

where factors not defined above are:

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

h_1 = porosity of the confining unit

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 a semiconfined aquifer (TOT < 40 years) from a confined aquifer (TOT >40 years).

Additional Notes Regarding CFR

In order to prevent a gross underestimation of the radius r_t of zones A, B5, and B10 (t = 2, 5, or 10, respectively), the lowest reasonable leakage rate, q_l, (or net recharge rate, I) should be used in these calculations. If the leakage (or recharge) rate is unknown, the effect of leakage (or recharge) should be neglected or more sophisticated tools should be used for delineation.

In many cases, Q is not a constant value, but varies with demand, build-out, etc. The California DWSAP specifies that the pumping capacity, Q, of the well is to be used in the above equations. The pumping capacity is the maximum rate at which the well can be pumped. Under certain circumstances, a water supplier may instead use the total annual production of the well in the highest of the previous three to five years (in ft^3/year) for calculations. Water suppliers are encouraged to consider future production levels if significant growth is expected to occur in the service area.

Simplified Variable Shapes for Sloping Aquifers: Modified CFR

As previously discussed, the assumption that most of the aquifer water contributing to a well originates from a cylindrical volume around the well is only appropriate in the immediate vicinity of a pumping well (up to 50–100 feet from the well), or if the regional aquifer gradient is negligible. If the potentiometric surface (for confined aquifer) or the water table (for unconfined aquifer) has a significant regional slope, then most of the contribution to the well is from the upgradient area and only a small amount comes from an area of limited size downgradient from a well (Figure 5). California DWSAP protection zones A, B5, and B10 therefore have an asymmetric shape around the well. As a preliminary assessment tool in porous media aquifers (but not in fractured aquifers), DWSAP allows the use of a modified calculated fixed radius method (modified CFR). In the modified CFR, the sizes of the cylindrical protection zones are exactly the same as in the CFR methods described above, but the center of the cylinder is moved upgradient by half the length of the radius, R_t, of the cylinder. For example, if the radius of Zone A is determined to be 1000 ft, the center of Zone A is 500 ft (half of 1000 ft) upgradient from the well (Figure 6). Calculations to determine the direction of groundwater flow must be submitted to DWSAP together with the computations for the size of the protection zones.

Other Simplified Variable Shapes for Sloping Aquifers

Another simplified variable shapes approach takes advantage of the fact that the size and shape of protection zones will be very similar within an area of a regional aquifer distinguished by a uniform gradient (similar direction and similar slope of the gradient throughout the area) and similar aquifer properties (porosity, hydraulic conductivity). Once the size and shape of the protection zones has been determined for one well (using any number of sophisticated tools), the same size and shape can be applied to delineate the protection zones of other wells in the area (Figure 7). However, the entire protection zone, not just the well itself, must be inside the area within which the aquifer gradient and aquifer properties have been determined to be uniform.

If aquifer characteristics vary in the area in which the shapes are to be used, then different combinations of aquifer parameters and pumping rates are tested to determine a large set of shapes. Tens or even 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 protection zone or 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 7). Table 1 identifies relative advantages and disadvantages of this method.

In California, no statewide set of "shapes" has been developed, due to the variety of hydrogeologic settings within the state. Local districts, communities, or groups of entities sharing a regional aquifer may consider developing a unified set of simplified variable shapes where local aquifer conditions allow (e.g., relatively uniform regional hydraulic gradient and similar aquifer conditions throughout the area of interest). The set of variable shapes must reflect all important regional and local aquifer conditions. It would be applied to individual community and non-community wells as a (recommended) minimum requirement for delineation of protection zones. Safety factors can be built in easily, by increasing the size of the shape by a given factor or distance. Because the simplified variable shapes reflect actual aquifer conditions (hydraulic conductivity, regional aquifer gradient, etc.), this method generally yields far more realistic protection zones than the CFR method.

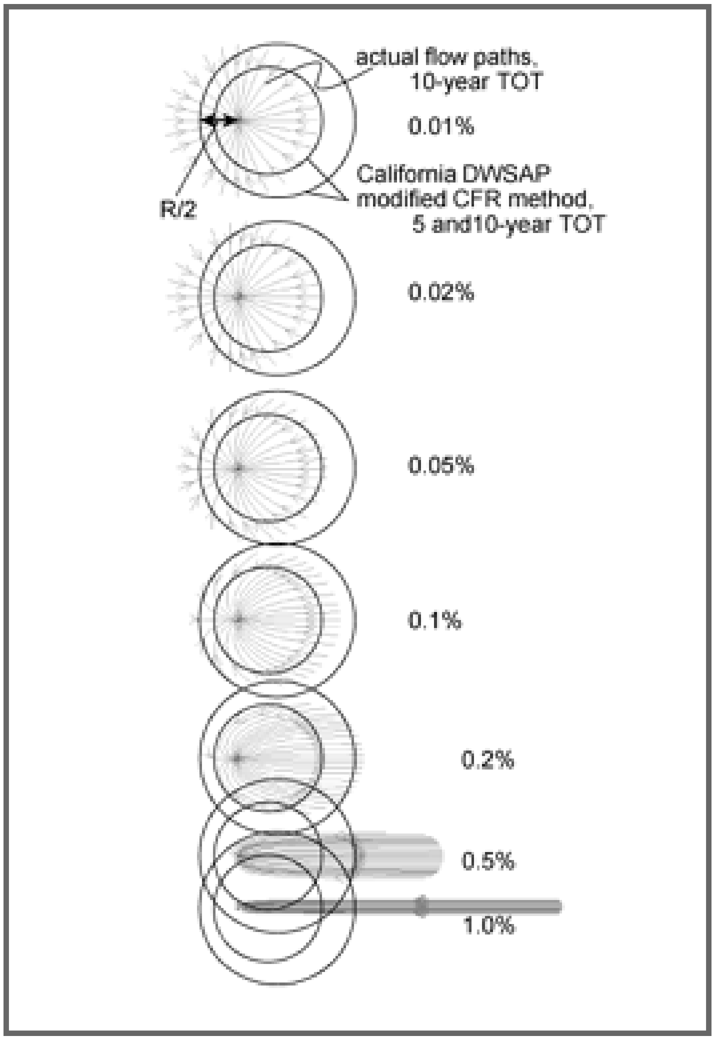

Figure 6: Same as Figure 5, but here the circles indicate the protection zones obtained from the California DWSAP modified CFR method. The CFR method works best at some low to intermediate groundwater level gradients (may vary by aquifer properties). At higher gradients it still provides a poor approximation of the protection zone actually needed.

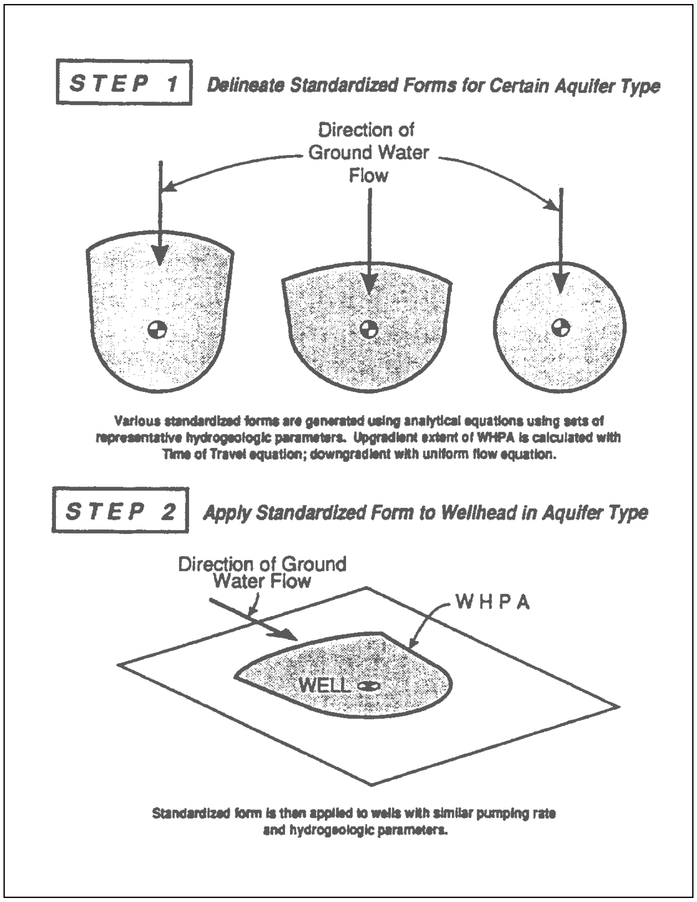

Figure 7: Delineation of wellhead protection area by simplified shapes method. (From EPA, 1994, Figure 4-4)

Analytical Methods: Overview

Arbitrary radius, CFR, modified CFR, and other simple shape methods represent only the most rudimentary "back-of-the-envelope" methods to delineate protection zones or WHPAs. Those methods are either arbitrary (i.e., without any relation to the well and aquifer characteristics) or based on simple mass balance considerations. Mass balance is indeed the most important tool for protection zone delineation. But beyond the definition of simple cylindric shapes, we must apply mass balance considerations *and* consider regional aquifer flow around the well. Flow in an aquifer is fundamentally governed by:

- Darcy's law, which says that the flow rate is proportional to hydraulic conductivity and the hydraulic gradient, and inversely proportional to porosity,
- the principle of mass conservation: what goes in must come out or result in a change of water storage—much like a bank account,
- aquifer geometry, aquifer boundary conditions, recharge, pumping rates and pumping location, and historic circumstances (initial conditions).

Together, Darcy's law and the "principle of mass conservation" (or "principle of continuity") provide the basis for all groundwater flow computations. They are expressed in the groundwater flow equation, which applies to practically all groundwater situations in porous media aquifers, and to many situations of fractured rock aquifers. All analytical and numerical methods for protection zone delineation are based on this equation. Why is there not just *one* solution to this equation? Because an important part of solving this equation mathematically is the historical water level condition. (In mathematics, this is called the *initial condition.*)

Another important part is the particular geometry of the aquifer (the *boundary conditions*), and the many different forms of recharge and pumping stresses distributed throughout the aquifer (*internal boundary conditions*). Each set of circumstances requires a particular solution of the groundwater flow equation.

There are two ways to solve the flow equation with all these conditions imposed on it: either through theoretical mathematical analysis, resulting in an analytical model (e.g., the Theis equation, which is commonly used to analyze pumping test results), or by computer modeling.

The many analytical models available in the literature describe solutions to the groundwater flow equation that were derived for specific idealized hydrogeologic settings and well configurations, and for specific aquifer boundary conditions and other conditions, such as partially penetrating wells, fully penetrating wells, confined aquifer, unconfined aquifer, multiple aquifers, leaky aquifer, etc. The mathematical complexity of some of these models challenges even the best mathematician. Regardless of complexity, though, all of the models simplify the aquifer into a more or less idealized simple geometric shape. (See, for example, Figures 2, 8). In some cases, an analytical model is satisfactory, but often a computer model is preferred—for example, when evaluating the effects of a complicated pumping pattern (e.g., Figure 9).

Both analytical and computer models for solving the groundwater flow equation can be used to determine the time of travel for delineating a wellhead protection area or protection zone. Again, the spectrum of available tools in either category (analytical or computer modeling) ranges from the simple to the difficult, depending on the degree of information available and the degree of accuracy desired.

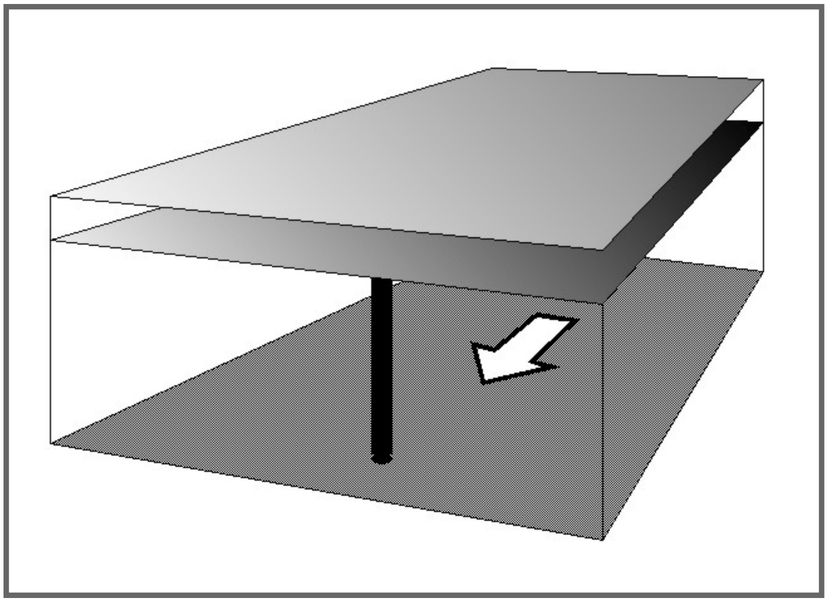

Figure 8: Geometric or analytical methods work best where the relevant extent of the aquifer can be described by simple geometry (uniform aquifer thickness, permeability, and groundwater flow direction).

Characterizing Aquifer Anisotropy & Heterogeneity

In some aquifers, hydraulic conductivity depends on the direction of flow, a phenomenon referred to as *anisotropy*. For example, at a given location the vertical hydraulic conductivity might be less than the horizontal hydraulic conductivity. In some cases, the horizontal hydraulic conductivity itself will vary, depending on the direction of flow. If horizontal anisotropy is significant, it should be accounted for in the delineation of the well recharge area.

Anisotropy should not be confused with aquifer *heterogeneity*. Heterogeneity refers to the fact that hydraulic conductivity varies from location to location and across depth. In other words, the hydraulic conductivity and other aquifer properties are spatially variable. Aquifer heterogeneity is a ubiquitous phenomenon. The question here is, does it matter much for the practical purpose of delineating the recharge area of a well? To answer that question, it helps to distinguish between regionally-varying changes in aquifer properties (*regional heterogeneity*) that can be mapped out, for example, on a 15-minute map of the area and the *local heterogeneity* that is observed over distances of inches, feet, or a few tens of feet.

If representative water level maps are available from a dense network of pumping wells or observation wells, those maps, in conjunction with information about aquifer properties (hydraulic conductivity and porosity), can be used to estimate and delineate the areas within which the time of travel (TOT) of water to a well is less than a given threshold (2 years, 5 years, 10 years).

But, in many cases, water table or potentiometric surface distribution are only known with limited accuracy, usually because individual wells are often sparsely distributed through an area, thousands of feet apart. Then, the first step in estimating TOT is to come up with an estimated map of the water table or potentiometric surface around the pumping well that reflects the cone of depression created by pumping around the well.

While the cone of depression (sometimes called *zone of influence*) is not the same as the recharge area, a good knowledge of its shape and size is an important factor in delineating the recharge area and the various TOT-based protection areas within the recharge area. Computations of drawdown in the vicinity of the well (by analytical, semi-analytical, or computer methods) is therefore often an integral part of determining the TOT-based protection zones.

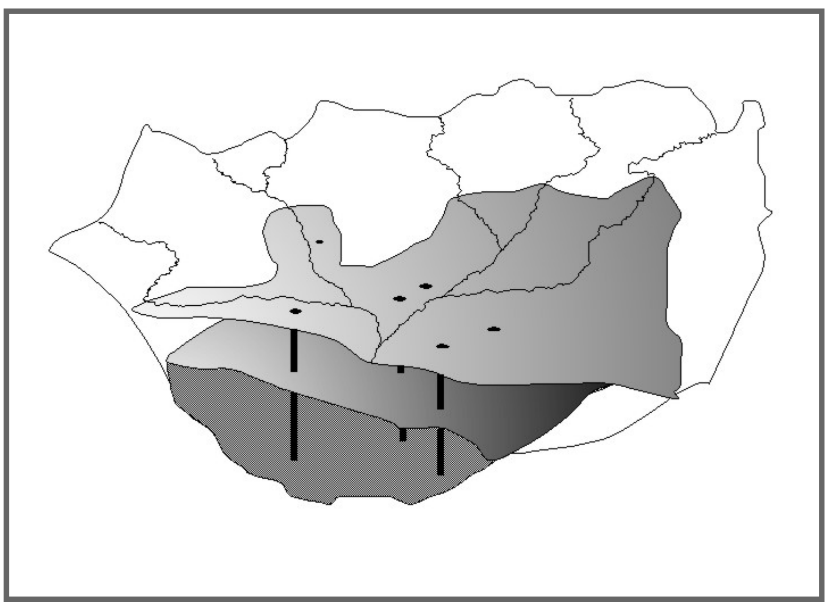

Figure 9: When the aquifer geometry is complex and multiple pumping wells are located near each other, numerical computer modeling may be the best tool for delineating groundwater protection zones.

Regional heterogeneity stems from differences in hydraulic conductivity that are observed between different strata of an aquifer, or between different subregions of the aquifer. An accurate potentiometric surface map is one of the most valuable ways to evaluate regional changes in aquifer properties. Hydrochemical maps also provide information that can be specifically related to the hydrogeology of an area and its regional variations. Aquifer tracer tests may indicate whether fracture flow zones (in hard rock aquifers) 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 from values measured by well tests. Geologic cross-sections, isopach maps (maps of the thickness of hydrogeologic strata), 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. Regional heterogeneity combined with the complex effects of pumping from multiple wells leads to complex protection zone shapes that are best evaluated with computer tools (Figure 9, Figure 10).

Local heterogeneity is difficult to describe in detail. Sediment type and hydraulic conductivity in both the horizontal and vertical direction changes rapidly with depth and distance—often over vertical distances of only a few inches to a few feet and over horizontal distances of a few tens of feet to a few hundreds of feet (Figure 11). This seemingly chaotic behavior of the aquifer structure at small scale can be observed, for example, in road cuts or in borehole logs.

Time-of-travel calculations for heterogeneous aquifers or for aquifers with significant secondary porosity may underprotect wellhead areas, because hydrodynamic 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 flow via fractures or conduits result in local velocities that are 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. When the potential for heterogeneity or hydrodynamic dispersion is high, it is necessary to choose higher-than-measured hydraulic conductivity values or to use values in the upper range of similar aquifer materials .

As a rule of thumb, all aquifers in California should be considered to be locally heterogeneous. *Fractured rock aquifers* are traditionally known to be highly heterogeneous. *Alluvial aquifers*—making up most of California's groundwater resources—are also highly heterogeneous, both at the local and regional scale. Alluvial fans and sediments have been built, eroded, rebuilt, and re-deposited in place over hundreds of thousands of years by river deposition, flooding, and channel erosion. Alluvial aquifers consist of variably thick, mostly localized intermixed layers and lenses of coarse, sandy, or gravelly river channel deposits, somewhat finer overbank deposits, and fine silty, clayey flood and lake bottom deposits. Interfingered with these are fine sandy eolian (wind blown) deposits, and hardened (calcified, or iron-fortified) ancient soil layers, hardpans, or caliche layers. The arrangement of highly

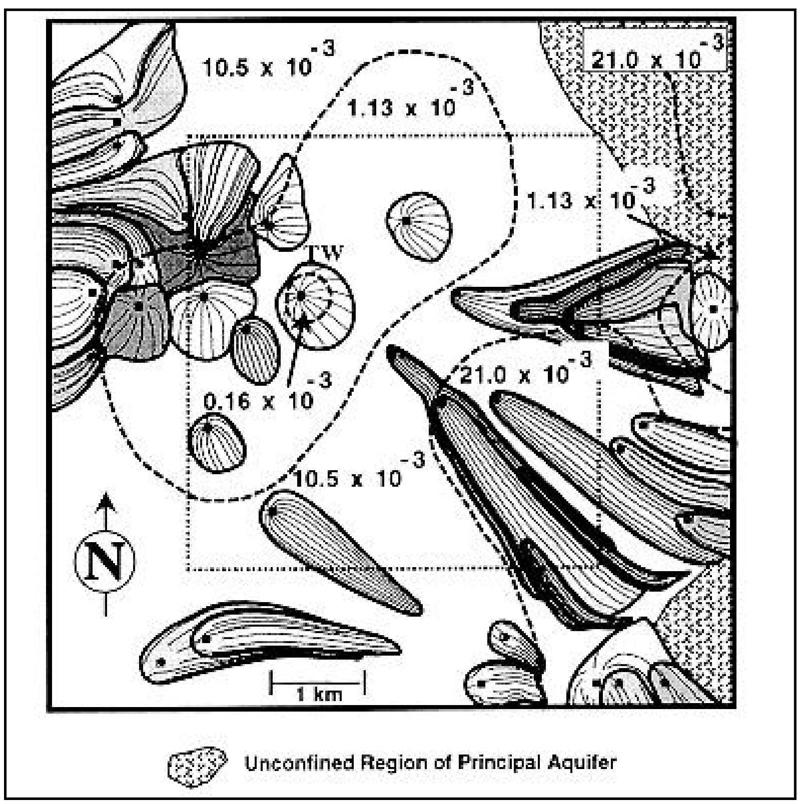

Figure 10: Fifteen-year TOT zones (shapes with flow lines) in a confined aquifer with a complex flow field. Contour lines delineate areas of varying hydraulic conductivities. (From Forster, C. B., T. E. Lachmar, D. S. Oliver, 1997)

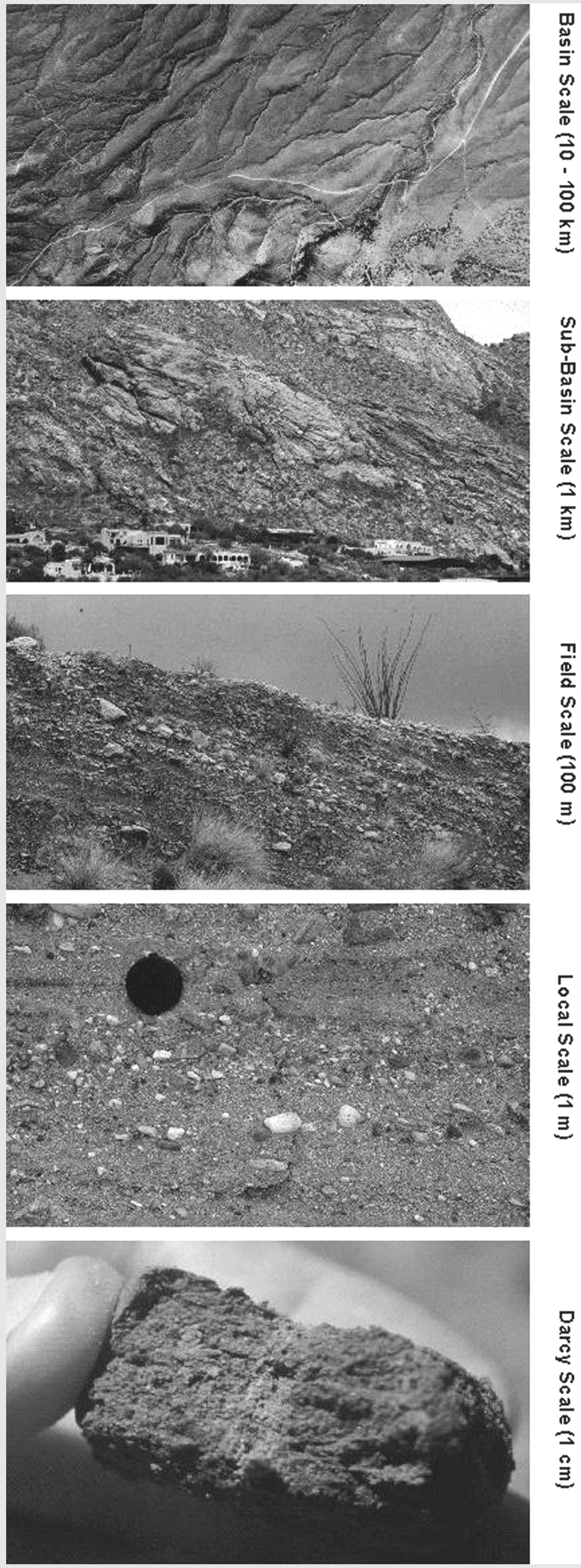

Figure 11: Illustration of aquifer heterogeneity at various scales. The top photo is an aerial photograph of mountain valley and basin aquifers. The remaining photographs are of vertical (or almost vertical) cross-sections through geologic material that can serve as a groundwater reservoir. The width of the cross-sections vary from several kilometers (top) to less than an inch (bottom), yet all exhibit patterns of heterogeneity.

permeable gravels and sands and of less permeable loams, silts, and clays in these alluvial sediment "packages" is very complex. The fastest and most significant transport occurs in channel-like sediment bodies consisting of sands and gravels, even if they make up as little as 15% to 20% of an aquifer (by volume). On the other hand, once contaminated, the part of the contamination that reached into the fine-grained sediments will slowly be flushed back out into the sands. That creates a long-lasting (years or decades) low-level "leak" of contamination from the low permeability parts of the aquifer to the higher permeability parts within the aquifer.

For purposes of assessing regional groundwater flow and of managing bulk groundwater flows, such heterogeneity can be safely ignored. Instead, a larger, integrated measure is used to describe the overall, regional hydraulic properties of the alluvial aquifer. But for purposes of source water delineation and contamination prevention, the complexity of the aquifer system imparts significant "chaos" upon the travel path and travel time of contaminants: some contamination will travel quickly along the interconnected, but complexly structured sandy, gravelly channel deposits, while a significant portion will be trapped in the less permeable clayey and silty clayey material interbedded between channel sediments. These low permeable sediments fill a large portion of the lateral distance between ancient channel beds (Figure 10).

The significance of local heterogeneity for well recharge area delineation can be summarized as follows:

- Contaminants travelling through the most permeable part of an aquifer have the shortest travel time to the well.
- Contaminants travelling though the most permeable part of an aquifer can reach a well from sources much further away than what might be expected based on estimates of average aquifer properties.
- Contaminants travelling through the most permeable part of an aquifer are generally subject to less microbial degradation and other natural attenuation processes (except dilution) than those travelling at slower speed through lower-permeability layers and sediment lenses.
- If contaminant transport through higher-permeability zones is of concern, the size of the TOT-based protection zones A, B5, and B10 should be increased to account for the faster travel velocity and longer travel distances of these contaminants.

It is important to recognize that using an average value for hydraulic conductivity in any of the simple methods described in this booklet is likely to overestimate the time of travel for some contaminants given a fixed distance. Hence, these methods may underestimate the extent of TOT zones A, B5, and B10, because contaminants will often travel faster in layers or channels of higher permeability or in fractures. For the purpose of wellhead protection, characterization and delineation of the most permeable groundwater pathways (and not the average) within a heterogeneous aquifer should guide the overall hydrogeologic delineation of the protection zones. For remediation purposes, on the other hand, the delay, diffusion, and attenuation of contaminants within the less permeable structures of an aquifer has great influence on the efficiency and the time horizon of a remediation project.

Methods that allow measurement or qualitative observation of the similarities and differences in aquifer characteristics across vertical or horizontal distances allow some assessment of whether an aquifer is homogeneous or heterogeneous. Table 4 summarizes a number of field methods that are commonly used or especially well suited for this purpose. Study of drill logs and geophysical borehole logs allows assessment of vertical changes in lithology, porosity, and permeability, as well as an assessment of the fraction of highly permeable sediments within the aquifer. 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. On alluvial fans, soil maps of the C horizon texture also provide a good indication of the fraction of highly permeable channel deposits within the fan.

If the CFR method is used, a conservative estimate of the heterogeneity-adjusted protection zone can be obtained by assuming that most of the pumped groundwater originates from the highly permeable zones (that is, from only a fraction of the total thickness). The radius of the protection zone must therefore reflect the reduced effective thickness of the aquifer. The adjusted CFR radius is (see also Table 5):

$$r_{adjusted} = r_{CFR} \cdot \text{sqrt}\,(100/f)$$

where:

$r_{adjusted}$: heterogeneity-adjusted CFR radius

r_{CFR}: radius obtained from the CFR method

f: fraction (in %) of highly permeable material within the heterogeneous aquifer or the screened well interval.

Similarly, the thickness, b, of an aquifer should be adjusted to reflect the effective thickness of the most permeable aquifer materials. The adjusted "effective" aquifer thickness is equal to the actual aquifer thickness

Table 4: Methods for Characterizing Aquifer Hetereogeneity

Method	Properties	Comments
VERTICAL VARIATIONS		
Drill logs	▪ Changes in lithology ▪ Aquifer thickness ▪ Confining bed thickness ▪ Layers of high or low hydraulic conductivity ▪ Variations in primary porosity (based on material description)	▪ Basic source for geologic cross sections ▪ Descriptions prepared by geologist preferred over those by well drillers ▪ Continuous core samples provide more accurate descriptions
Electric logs	▪ Changes in lithology ▪ Changes in water quality ▪ Strike and dip (dip meter)	▪ Requires uncased hole and fluid-filled borehole
Nuclear logs	▪ Changes in lithology ▪ Changes in porosity (gamma-gamma)	▪ Suitable for all borehole conditions (cased, uncased, dry, or fluid-filled)
Acoustic and seismic logs	▪ Changes in lithology ▪ Changes in porosity ▪ Fracture characterization ▪ Strike and dip (acoustic televiewer)	▪ Requires uncased or steel-cased hole and fluid-filled hole
Other logs	▪ Secondary porosity (caliper, television or photography) ▪ Variations in permeability (fluid temperature, flowmeters, single-borehole tracing)	▪ Requires open, fluid-filled borehole ▪ 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		
Method	**Properties**	**Comments**
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
Geologic maps and cross-sections	▪ Changes in formation thickness ▪ 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	▪ Requires considerable skill at interpreting geologic and hydrogeologic features
Surface geophysics	▪ Changes in lithology (seismic) ▪ Structural features (seismic, GPR, gravity) ▪ Changes in water quality or containment plume detection (ER, EMI, GPR)	▪ Distinctive strata with large areal extent required

from EPA, 1994

Table 5: How to Adjust CFR Radius and Compute "Effective Thickness" When Fraction of Aquifer Is Highly Permeable

If f =	then multiply r_{CFR} by	and multiply thickness, b, by
10%	3.2	0.1
15%	2.6	0.15
20%	2.2	0.2
25%	2.0	0.25
33%	1.7	0.33
40%	1.6	0.4
50%	1.4	0.5
66%	1.2	0.66
80%	1.1	0.8

Note: This assumes that K for the highly permeable material is more than one order of magnitude greater than for the rest of the aquifer.

multiplied by the fraction of highly permable aquifer material (see Table 5).

We also need to adjust the hydraulic conductivity, K, used in the analytical equations in this booklet. When TOT-based protection zones (DWSAP zones A, B5, B10) are delineated, the hydraulic conductivity used in calculations must be that of the most permeable strata. Because the travel time is inversely proportional to K, the length of a TOT-based protection zone will be significantly larger after accounting for heterogeneity in this manner.

The above "effective thickness" method is best when the most highly permeable strata are at least one order of magnitude more permeable than the remaining aquifer. Geostatistical methods have become readily available for a more detailed analysis of aquifer heterogeneity, particularly for estimating regional and subregional changes and variability in hydraulic properties and their effects on WHPA areas. Those approaches, however, require a relatively high density of subsurface observations, which may not be available in potential wellhead protection areas. Their application requires the use of a specialized consulting service. Based on geostatistical data, delineation of a protection zone can be made on a "risk" basis or "probability" basis. Figure 12 illustrates an application where statistical and geostatistical tools have been used to define the probability that any particular location around a well is part of the wellhead protection area.

Simple Analytical Methods for Delineating TOT & Recharge Zones

In this section we provide a brief overview of a few simple analytical methods that are available for the delineation of wellhead protection zones. (We have already discussed the simplest analytical tool: the calculated fixed radius method. Some of the following tools are merely extensions of the CFR method.) The important thing to remember is this: choose a method whose governing equation is based on assumptions that are appropriate for the well and aquifer in question. Also, note that the equations covered here do not consider hydrodynamic dispersion or contaminant retardation processes. (For more information about those processes, see the booklet on groundwater contamination.) Where contaminants are not subject

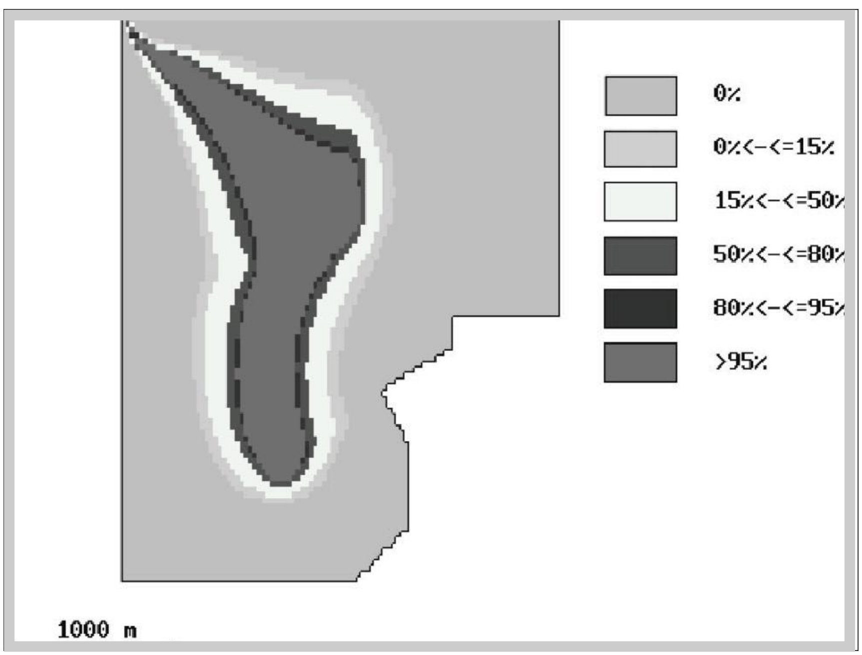

Figure 12: Stochastic wellhead protection zone computed for a heterogeneous aquifer (from: Kunstmann and Kinzelbach, 2000). The percentages in the legend are the probability that a particularly colored region is within the actual source zone of the well (located near the bottom of the "plume" shape). Large parts of the area are certainly not in the source area (0% probability, light gray). Closer to the source, the likelihood that a given location is part of the source area increases quickly from 0% to over 95%.

to attenuation (for example, salts, chlorides, nitrates, MTBE), calculating the time of travel should provide a reasonably accurate delineation of the area at risk.

Delineating Protection Zone for a Well in an Aquifer with Uniform Sloping Gradient

The effect of a uniform slope on the shape of the 5-year and 10-year protection zones is demonstrated in Figures 5 and 6. The shape of these protection zones is almost circular in an aquifer with very low slopes (< 0.05%), but the shape becomes longer and narrower at steeper slopes and most of the time-of-travel (TOT) zone will be upgradient of the well and not around the well. When the slope is significant (0.1% or greater), it should be accounted for in the delineation of the TOT zones.

The so-called uniform flow equation has been widely used for the delineation of wellhead protection areas and recharge zones where a sloping regional hydraulic gradient creates an asymmetrical cone of depression (Figure 13a). The recharge zone (zone of contribution) is defined using two equations originally developed in 1930 by Forchheimer:

$x_{limit} = 1{,}440 \cdot Q / (2\pi\ K\ b\ i\ )$ (3)

and

$y_{limit} = 1{,}440 \cdot Q / K\ b\ i$ (4)

where (see also Figure 13b):

x_{limit}: furthest point downgradient from the well within the cone of depression, ft

y_{limit}: maximum width of the upgradient recharge zone, ft

Q: average pump discharge, gpm

K: hydraulic conductivity, gpd/ft^2

b: thickness of the aquifer, ft (the well is assumed to penetrate the entire aquifer)

i: average regional gradient of the groundwater level (or potentiometric surface)

These simple equations define the downgradient flow boundary, x_{limit} , and the maximum width, y_{limit}, of the upgradient recharge zone, respectively (Figure 13b). But how would this method be used for delineation? Equations 3 and 4 provide the width of the recharge area and the downslope extent of the cone of depression. In the upgradient direction, TOT zones and the complete recharge area can be determined by other means:

1. TOT estimates can be made (discussed in the sections that follow) to draw an approximate TOT contour within the shape delineated by x_{limit} and y_{limit} and the upgradient time-of-travel isochrone (Figure 13b). This alternative would used in California for delineating zones A, B5, and B10.
2. The entire recharge area can be delineated by extending the flowlines that mark the

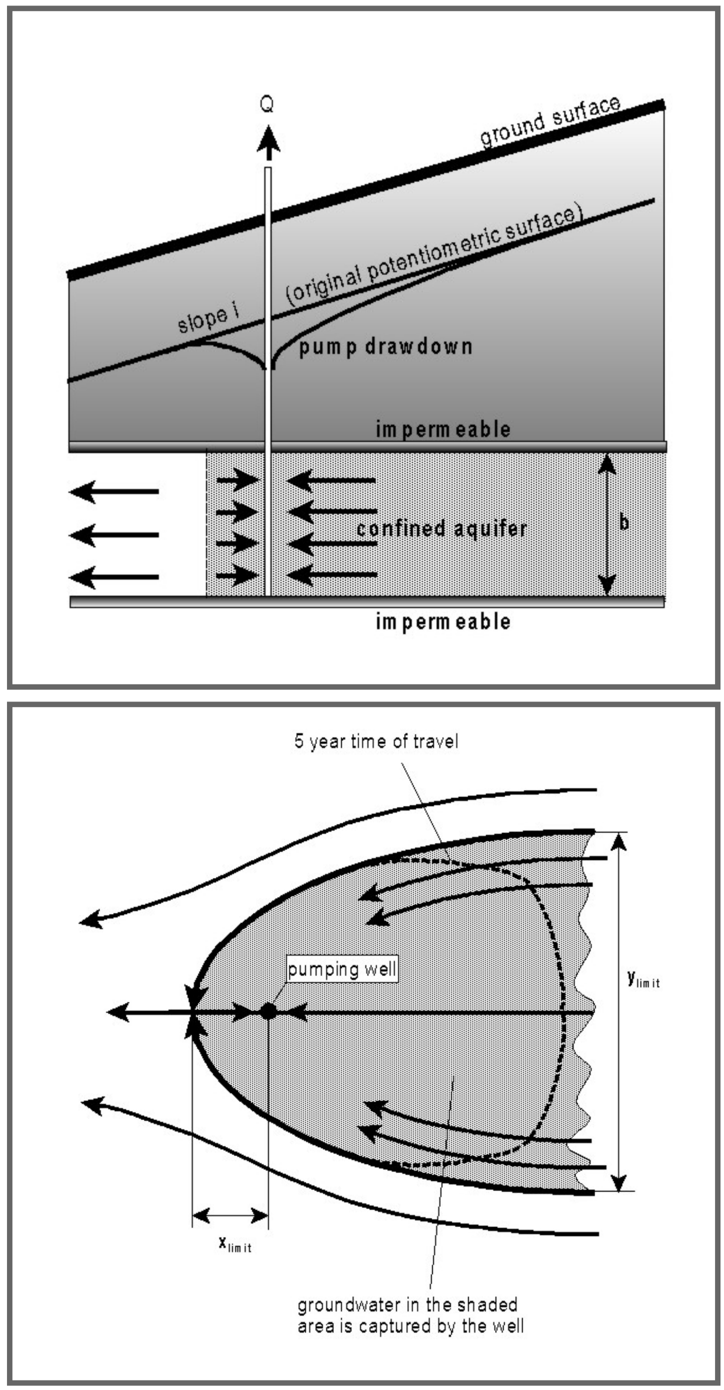

Figure 13: Flow to a well in a uniformly sloping potentiometric surface: (a) cross-section (upper), and (b) plan view (lower). (Modified from EPA, 1994, Figure 4-10)

boundaries of y_{limit} all the way back ("uphill") to a ground water divide or other aquifer boundary.

The uniform flow equation applies, strictly speaking, only to confined aquifers. But, as in the CFR method, the above equations can also be used for unconfined aquifers, using the saturated thickness of the aquifer, provided that drawdown is less than 10 percent of the saturated thickness of the aquifer. The above equations do not account for leakage. By neglecting leakage, this model will define larger TOT protection areas than are necessary.

Delineating TOT Zones within Uniform Regional Gradient

The time of travel (TOT) from a distance x to the well is computed by considering the groundwater velocity within that area. Groundwater velocity estimates are obtained by applying Darcy's law, which describes the groundwater velocity as a function of the hydraulic conductivity, porosity, and groundwater hydraulic gradient:

$$v = 48.79\ K\ i\ /\ n \qquad (5)$$

where:

v = average interstitial (linear) velocity, ft/yr

K = horizontal hydraulic conductivity, gpd/ft^2

i = approximate horizontal or radial hydraulic gradient, averaged over the area of interest, ft/ft

n = aquifer porosity; usually from 0.1 to 0.3 (10%–30%); where unknown, the California DWSAP specifies to use 20%

If the aquifer is relatively homogeneous and the slope of the hydraulic gradient is uniform, then the velocity (from Equation 5) is computed after using a potentiometric map of the aquifer to measure the hydraulic gradient. If K and n values are not available, preliminary estimates of K and n can be obtained based on the type of aquifer material. Once average velocity has been computed with Equation 5, the distance that groundwater travels during a given time (e.g., 2 years, 5 years, 10 years) is calculated as follows:

$$d = t\ v = 48.79\ t\ K\ i\ /\ n \qquad (6)$$

where:

d = the distance, in feet, that water travels during t years

v = average linear (pore) velocity, ft/yr

t = specified time of travel, years

Vice versa, the time, in years, needed for groundwater to travel a distance d, in feet, between two points where the potentiometric slope, i, is uniform can be calculated by rearranging Equation 6:

$$t = d\ /\ v = d\ n\ /\ (48.79\ K\ i) \qquad (7)$$

Recharge Zone for Negligible Regional Gradient, Uniform Recharge

When the regional gradient is very low (< 0.0005 or 0.001) and an aquifer receives either uniform recharge through the unsaturated zone (unconfined aquifer), through the upper or lower confining aquitards (confined aquifer), or through overburden (confined and semi-confined aquifers), the recharge area to the well is approximately of circular shape. The extent of that recharge area can be determined from simple mass balance: in the long term (that is, once the system has reached steady-state), the discharge Q from the production well will equal the average recharge or leakage into the aquifer within that circular recharge area. In an unconfined aquifer, the total recharge into the recharge area is equal to the recharge rate, I, times the area of the circle delineating the recharge area:

$$Q = I\ \pi\ r^2 \qquad (8)$$

where:

Q = annual pumpage, ft^3/yr

r = radius of the recharge area, ft

I = infiltration, ft/yr

In a confined aquifer, the leakage into the aquifer is equal to the vertical hydraulic conductivity of the confining layer, K_v, multiplied by the average pressure gradient across the confining layer and multiplied by the recharge area:

$$Q = 48.79 \cdot K_v\ i\ \pi\ r^2 \qquad (9)$$

where:

Q = annual pumpage, ft^3/yr

K_v = vertical hydraulic conductivity in the confining unit, gpd/ft^2

i = average pressure gradient across the confining unit

r = radius of the recharge area, ft

Suggested K_v values for silt and clay (in the confining layer) are on the order of 0.01 gpd/ft^2. A spreadsheet for computing the radius of recharge (delineation.xls) is included on the accompanying CD-ROM.

This scenario is essentially identical to the CFR method, except that Equations 8 and 9 establish the entire recharge area for a well and not just a zone with a fixed time of travel (Equation 2). Also, note that Equation 2 provides the distance from the well, given a specified time of travel. To calculate the time of travel from a given distance, r, to the well, we rearrange Equation 2 and obtain:

$$t = \pi r^2\ b\ n\ \ /\ [70{,}258\ x\ Q - \pi\ r^2\ (q_1 + q_2) \qquad (10)$$

where:

t: time of travel, years

r: distance from the well for which time of travel is being computed, ft

b: thickness of the aquifer, ft (assumed to be the same as length of well screen)

n: porosity of the aquifer

Q: pumping rate at the well, gpm

q_1: recharge rate from the unsaturated zone or leakage rate from the upper confining layer, ft/yr

q_2: recharge rate from the lower confining layer, ft/yr

Like the CFR method, Equation 10 applies to confined, leaky confined, or unconfined aquifers. However, it can be used for unconfined aquifers only if the total drawdown at the pumping well does not exceed 10% of the aquifer thickness. If total drawdown exceeds 10%, vertical flow near the well affects the travel time and Equation 10 does not apply.

Note that instead of using Equation 10, one could compute the TOT by (1) dividing the pathway to a well into segments each of which has approximately uniform potentiometric slope, (2) applying Equation 7 to each segment, and then (3) adding up the individual travel times.

The following example illlustrates how to calculate the velocity and time of travel for a chemical contaminant in an aquifer with straight (uniform) slope throughout the area of interest (and negligible cone of depression, negligible heterogeneity).

Example: A liquid substance containing chloride spills and leaks into the ground. 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 20%. The water level in a well at the spill lies at an altitude of 1,525 feet and, at a well one mile (5,280 feet) directly downgradient, is at 1,515 feet. The potentiometric slope, i, is therefore 10 feet per 5,280 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 from Equations 7 and 9:

$v = 48.79 \cdot (2{,}000 \text{ gpd/ft}^2) \cdot (10 \text{ ft} / 5{,}280 \text{ ft}) / 0.20 = 924 \text{ ft/yr}$

$t = 5{,}280 \text{ ft} / (924 \text{ ft/year}) = 5.7 \text{ years}$

The five year time-of-travel (TOT) zone is at the following distance from the downgradient well (Equation 8):

$d = 924 \text{ ft/year} \cdot 5 \text{ years} = 4{,}620 \text{ feet}$

The spill is therefore outside the 5-year zone.

Note: 1 gpd/ft^2 = 48.79 ft/year

Significant Cone of Depression Within a Sloping Regional Potentiometric Surface

In most practical scenarios, when computing time of travel, the regional groundwater table gradient cannot be neglected (Figure 5). In those cases, the cone of depression will be asymmetric, with drawdown extending farther upgradient than downgradient. An equation that accounts for the actual conical shape of the cone of depression within the regional groundwater flow field is given by Kreitler and Senger (1991). The equation allows us to compute the travel time from a point x directly upgradient from the well to the well itself:

$$t_X = n / K i \, [r_X - Z \ln \{1 + r_X/Z\} \qquad (11)$$

where:

$Z = Q / 2 \pi K b i$

t_X = time of travel from point x to a pumping well, in years

n = porosity

r_X = distance, in feet, over which groundwater travels in t_X; r_X is positive (+) if the point is upgradient, and negative (–) if downgradient

Q = pumping discharge, ft^3/yr; (note: Q in ft^3/yr = 70,258 · Q in gpm)

K = hydraulic conductivity, ft/yr; (note: K in ft/yr = 48.79 · K in gpd/ft^2)

b = aquifer thickness, feet (complete well penetration is assumed)

i = hydraulic gradient, ft/ft

The above equation computes travel time to the center of the well and assumes that the well radius is small relative to the distance r_x (<5%). Calculation of distance for a specific time of travel requires trial-and-error calculations, using different values for distances, until the equation yields the desired time of travel. This can be done easily using a computer spreadsheet. (Equation 11 is implemented in the spreadsheet "delineation.xls", included on the accompanying CD-ROM disk.)

Equation 11 is used after the recharge area has been delineated around a well located within a uniform regional hydraulic gradient. The main weaknesses of this equation are:

- It only provides distance for time of travel along a line through the pumping well and parallel to the regional hydraulic gradient (i.e., one point upgradient). Where equipotential lines on a potentiometric map are not straight lines, this would be the shortest flow line upgradient.

- It does not take into account recharge from the surface in unconfined aquifers or vertical leakage into semiconfined aquifers.

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

Hydrogeologic Mapping & Analysis

Hydrogeologic mapping provides a valuable complement to the simpler methods for delineating protection zones or wellhead protection areas. In addition, it is a necessary precursor to more complex numerical modeling of ground water flow using computers. Figure 14 illustrates WHPA delineation using geologic contacts and ground water divides as the key elements of hydrogeologic mapping. Potentiometric maps and methods for measuring aquifer parameters are also essential parts of hydrogeologic mapping.

Hydrogeologic mapping and analysis should be done only by experienced, professional groundwater specialists. The purpose of this booklet is to provide general conceptual guidance on this technique for those preparing, planning, managing, subcontracting, or reviewing work related to delineation of protection zones. More detailed information about the method can be found in some of the references listed at the end of this booklet.

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.

Soils & Geomorphology

The character and distribution of soils and landforms are major considerations in hydrogeologic mapping. This is especially true for lands within and adjacent to California's mountain ranges. Unconfined aquifers develop in unconsolidated materials and lie relatively near the land surface. In such settings, the water table generally follows the land surface, although with more subdued relief. Recharge areas are generally located in upland areas, and ground water divides tend to coincide with surface watershed boundaries.

The narrow valley bottoms and floodplains within California's mountainous regions that feature perennial streams (primarily in Northern California) represent groundwater discharge areas (i.e., groundwater discharges into streams and other surface water bodies). As these streams and rivers enter the larger California valleys and basins, they become a major source of groundwater recharge.

In California's rangelands and uplands, soils and topography determine how much precipitation infiltrates into the ground to recharge groundwater, and how much runs off to enter surface streams. Highly permeable soils and flat topography favor infiltration; less permeable soils and steep slopes promote surface runoff.

In the larger basins and valleys, which have predominantly flat topography, factors other than soil type are the primary controls on recharge rates and groundwater discharge. One such factor is *land use.* We discuss land use in more detail later in this booklet.

Geology

Geology provides the physical framework for the flow of ground water. Porosity (primary and secondary), storage coefficient, and permeability (hydraulic conductivity) are largely a function of the geologic

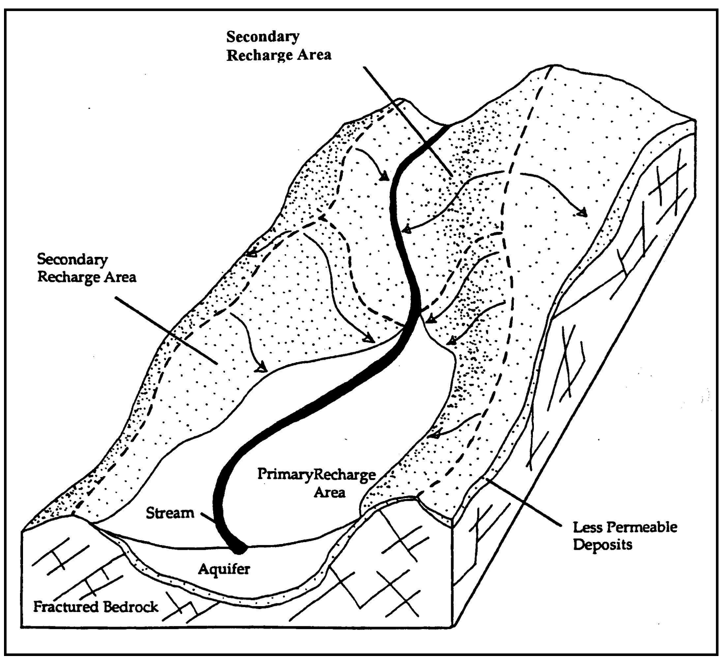

Figure 14: Illustration of the concept of recharge area (primary recharge area) and source area (secondary recharge area). (From California DWSAP, Figure 6-2)

materials present. Stratigraphy (the relationships between layered geologic materials) affects local and regional ground water flow by the distribution of strata of relatively higher and lower permeability. It defines the sequence of aquifers, aquitards, and aquicludes as well as their geographic extent, thickness, dip (angle of tilt) and strike (direction perpendicular to direction of tilt). In fractured rocks and consolidated materials, structural features such as folds or fractures—remnants of ancient or recent tectonic processes—can block or change the direction of groundwater flowing through nearby horizontal sediments. Displacement of sediments by faulting can provide zones of increased permeability, as a result of fracturing. It can just as easily create aquifer boundaries. These may occur, for example, where impermeable strata block the flow of water through permeable strata. Secondary *fracture porosity* results primarily from tectonic stresses.

Hydrology

Although the focus of hydrogeologic mapping is on groundwater, the occurrence and flow of groundwater 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 closely connected to the hydrologic cycle.

It is often useful to prepare a regional groundwater balance at the onset of a groundwater project. The overall groundwater budget provides a framework for the conceptual understanding of groundwater flow within the area of interest.

For a typical California groundwater basin, the major components of the hydrologic balance include: effective precipitation, irrigation applications, crop water demands (evapotranspiration), municipal and industrial water demands, surface water imports and exports, surface water inflows and outflows into the area of interest, pumping demands, average recharge from precipitation and irrigation to groundwater, intentional recharge, recharge from rivers and canals, and groundwater discharge to rivers. Examples of a hydrologic balance are shown in Figure 15 and Figure 16. The "California Water Plan Update" (DWR Bulletin 160-98) contains an overall sketch of the water balance within the state's major regions.

Mapping of potentiometric surfaces is another important part of the hydrologic characterization. For the purposes of WHPA delineation, confined aquifers that are distant from their areas of surface recharge can be considered to be semi-isolated from the hydrologic cycle, provided that they are highly confined. This may greatly simplify the analysis of the groundwater flow system.

Hydrochemistry

Data on water quality can provide valuable insights into the hydrogeologic system. 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 are especially important if the potential for attenuation of contaminants is being considered in the WHPA delineation process.

Land use. Land use is a major component in determining aquifer recharge and groundwater pumping requirements. The largest pumpers of groundwater in California are cities and agricultural users. Knowing the urban and agricultural water requirements for an area, and the degree to which those requirements are met by surface water deliveries versus groundwater pumping, greatly helps us to understand the hydrologic balance of a groundwater basin. Most importantly, while pumping discharge from aquifers is a critical component of the groundwater budget, few records of actual pumpage typically exist in California.

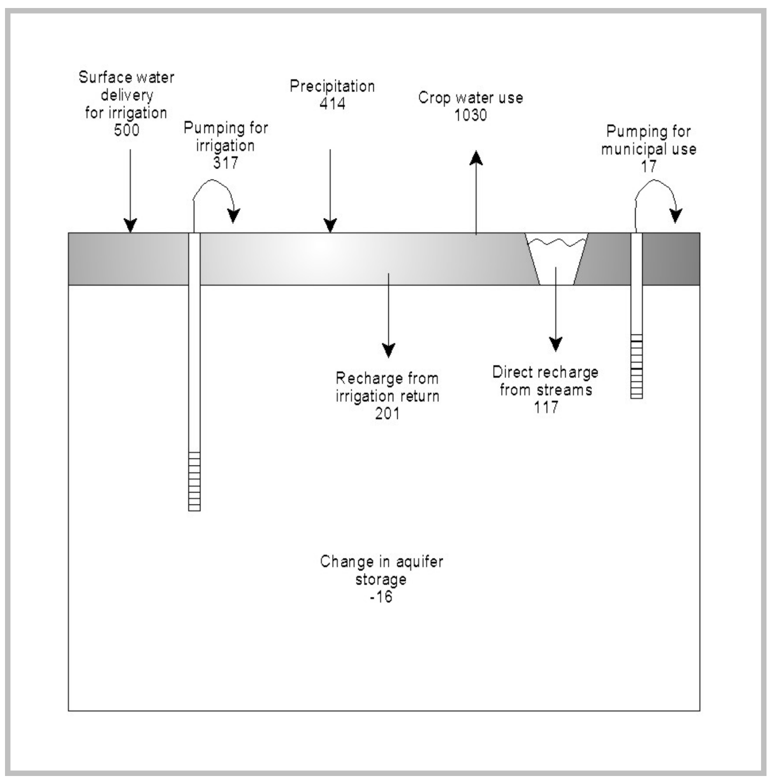

Figure 15: Water balance for a 550,000 acre groundwater basin on the southeast side of the semi-arid San Joaquin Valley, California. Numbers indicate annual fluxes of water in thousand acre-feet.

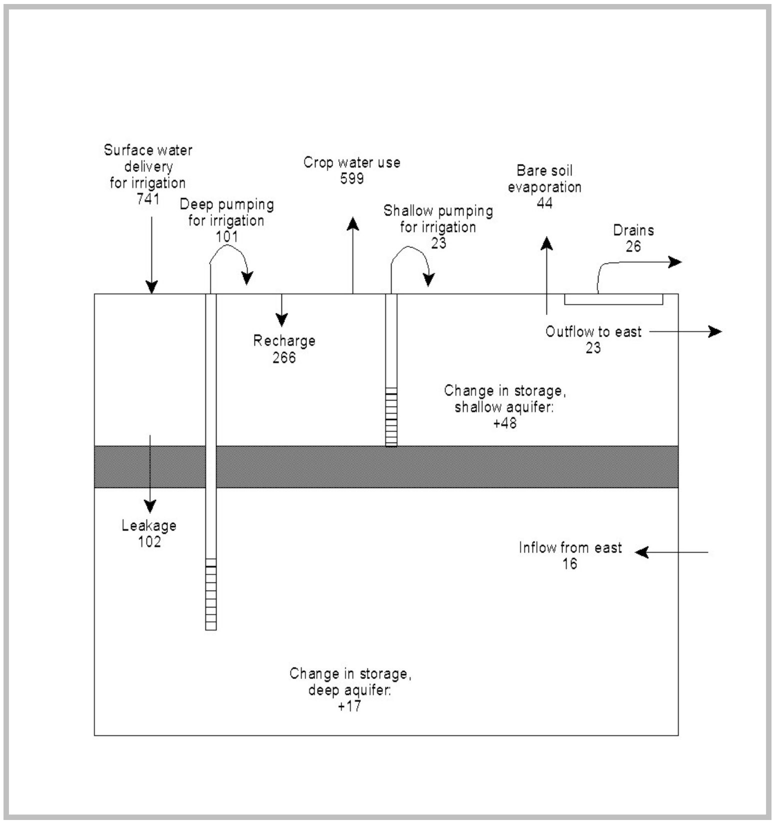

Figure 16: Water balance for a groundwater basin on the west side of the San Joaquin Valley, California. (Modified from Belitz and Phillips, 1995)

Groundwater pumpage must therefore be inferred from power records (electricity or fuel consumption of ag well pumps is a significant portion of rural power consumption) or by difference between water demands (ag or urban) and surface water deliveries. The latter is the preferred method when surface water deliveries and consumptive use (for evapotranspiration) are well known.

Cities and agriculture are not only dominant users of groundwater, they also can be significant rechargers of groundwater. Many cities in central and southern California recharge their groundwater by discharging treated, secondary wastewater effluent into infiltration basins. Some cities also have built basins specifically for storing surface water deliveries or for storing stormwater runoff; those basins also recharge groundwater aquifers.

Most of California's agriculture relies on irrigation. Even the most efficient irrigation system will require some water leaching, leading to significant groundwater recharge from irrigation.

In municipal areas and in low-elevation, irrigated agricultural areas throughout California, recharge of groundwater by precipitation is almost negligible when compared to intentional (basin) recharge and to the recharge of groundwater by crop irrigation.

Numerical Computer Modeling

Where the aquifer geometry cannot be described by a simple conceptual model (e.g., Figure 8), it is advantageous to explicitly account for the complex aquifer geometry and for the complex history of stresses that have been imposed on an aquifer (e.g., Figure 9). For that, computer models based on numerical methods have become very popular. They solve the same fundamental equation(s) as analytical models—and therefore involve no more and no less "wizardry" than analytical models. But unlike analytical models, computer models can deal with very complex, non-ideal boundary conditions, pumping well distributions, spatially non-uniform aquifer properties, etc. While not a perfect replica of the "real" aquifer, a numerical computer model allows a much better and more truthful representation of the complex architecture and workings of an aquifer than does an analytical model. In a computer model, aquifers can have complex shapes, be of variable thickness, be only partially confined, or have aquifer properties that vary spatially. Complex pumpage or recharge patterns that vary over time and space can also be modeled (Figure 17).

As with most other computer software, groundwater modeling software is advancing at a rapid pace. Many different kinds of groundwater modeling programs are available. The strict division between "analytical models" and "computer models" has been blurred with the introduction of computer software that utilizes analytical models both to analyze graphically and to illustrate (e.g., wellhead protection areas displayed directly on a computer). Another example of an analytical tool implemented on the computer is the spreadsheet "delineation.xls" (see accompanying CD-ROM disk). Computer software based exclusively on analytical methods (i.e., mathematical solutions) are common for the analysis of aquifer test data, but also for the delineation of wellhead protection areas. Because of their generally easy-to-use PC Windows® interface, such software programs often are a potentially low-cost alternative to more complex computer models.

What has traditionally been referred to as "computer models" are so-called numerical methods or numerical computer models (as opposed to analytical methods or analytically-based computer models). Numerical techniques allow the computer modeler to design complex "virtual" copies of a real aquifer by discretizing the aquifer into small boxes (usually referred to as "cells") of variable size and shape, depending on the particular numerical method (Figure 17). The principle is the same as that used for many other computer software applications that provide a virtual view of the world (in two or three dimensions), be it a flight-simulator game, a virtual garden design program for the home gardener, or professional engineering design software.

The discretization allows the aquifer to have any desired three-dimensional shape. Rivers, lakes, streams (all of which are typically linked to groundwater), fields (recharge from irrigation), wells, and contaminant sources can be implemented in arbitrary configurations by assigning certain cells to represent these sinks or sources of water and contaminants. Because each small cell can be assigned different aquifer properties, multiple aquifer layers and regional or even local differences (heterogeneities) in aquifer properties within each aquifer can be implemented by assigning the appropriate numbers to the individual cells. The accuracy and detail with which this virtual aquifer represents reality is limited only by the number of cells that the numerical model can contain and by the geologic and hydrologic knowledge available to provide the appropriate properties and sink-source strengths to the individual cells representing the aquifer, aquitards, aquifer boundaries, rivers, wells, fields, etc.

Numerical aquifer models currently developed by the hydrogeologic consulting industry contain from several thousand to over 1,000,000 cells.

A lower number of cells (1,000 to 100,000) is typically used in site studies or in regional applications where local heterogeneity of aquifer properties can be ignored. A relatively small number of cells may also be appropriate if the model is only two-dimensional (i.e., representing only the horizontal flow processes of an aquifer).

A higher number of cells (> 100,000) is needed if local heterogeneities are modeled in significant detail or if the region to be modelled is very large and has a complex three-dimensional shape. Numerical modelers refer to these cells either as *finite difference* cells or *finite element* cells, depending on the particular numerical discretization and computing method used. Other methods (e.g., *finite volume* method, *boundary element* method) are used too, and each has its own discretization scheme.

Different methods vary in their computational efficiency and in the accuracy with which the physical processes of groundwater flow and contaminant transport can be imitated by the computer. Some methods are used only for particle or contaminant transport and not for groundwater flow (e.g., *particle tracking* method, *random walk* method). Groundwater modeling software differ not only by the numerical methods they employ, but also by the types of physical and chemical processes that they can simulate. Table 6 contains a classification of groundwater flow and transport software by the type of processes modeled.

The greater the number of cells and the more complex the type of processes modeled, the more computer power is needed to run the model. In many applications, particularly those involving only groundwater flow modeling (but not contaminant transport modeling), the actual computing time for simulating many months or years of groundwater flow has become almost negligible (measured in seconds or minutes), even on a standard office PC. However, if the computer model

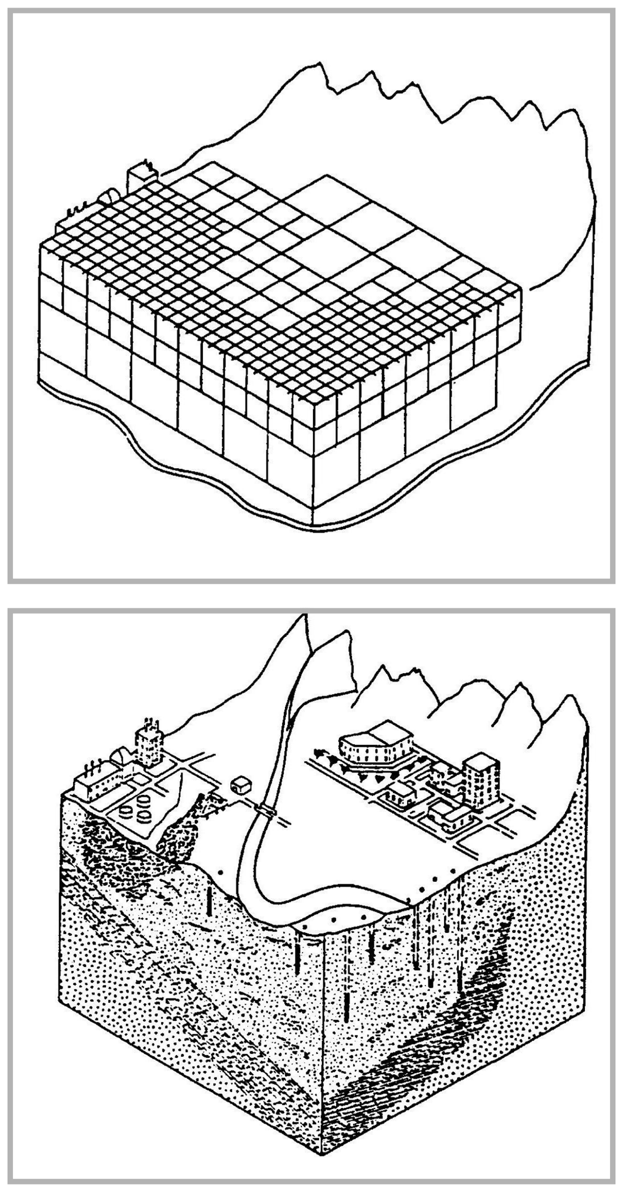

Figure 17: (a) Three-dimensional grid to model groundwater flow in (b) complex geologic settings with pumping wells downgradient from potential contaminant sources. (From EPA, 1994, Figure 6-1)

needs to track complex transport patterns, interactions between different contaminants, and chemical reactions, numerical efficiency is important, as computation time may quickly be on the order of hours or even days. The main limitation in the design of numerical computer models today is not computer power, but knowledge of the aquifer geometry, aquifer properties, aquifer boundary conditions, sink-source strength, and hydrologic history leading up to today's water table conditions. Preparing a computer model therefore takes considerable expertise and time and is considered a specialized field of hydrogeology.

Table 6: Computer Codes for Groundwater Flow & Transport

FLOW (POROUS MEDIA)

Type of Code	Description/Uses
Saturated	▪ Simulates movement of water in saturated porous media. Used prima-
Variable saturated	▪ Simulates unsaturated flow of water in vadose (unsaturated) zone. Used

SOLUTE TRANSPORT (POROUS MEDIA)

Type of Code	Description/Uses
Dispersion	▪ Simulates transport of conservative contaminants (not subject to retardation) by adding a dispersion factor into the flow calculations. Used for non-reactive contaminants, such as chloride, & for worst-case analysis
Retardation/degradation	▪ Simulates transport contaminants that are subject to partitioning or transformation by the addition of relatively simple retardation or degradation factors to algorhythms for advection-dispersion flow. Used where retardation & degradation are linear with respect to time and do not
Chemical-reaction	▪ Combines an advection-dispersion code with a hydrogeochemical code to simulate chemical speciation & transport. Integrated codes solve all mass momentum, energy-transfer, & chemical reaction equations simultaneously for each time interval. Two-step codes first solve mass momentum & energy balances for each time step & then re-equilibriate the chemistry using a distribution-of-species code. Used primarily for mod-

HYDROGEOCHEMICAL

Type of Code	Description/Uses
Thermodynamic	▪ Processes empirical data, so that thermodynamic data at a standard refernce state can be obtained for individual species. Used to calculate reference state values for input into hydrogeochemical speciation cal-
Distribution-of-species (equilibrium)	▪ Solves a simultaneous set of equations that describe equilibrium reac-
Reaction progress (mass-transfer)	▪ Calculates both the equilibrium distribution of species (as with equilibrium codes) & the new composition of the water as selected minerals

SPECIALIZED

Type of Code	Description/Uses
Fractured rock	▪ Simulates flow of water in fractured rock. Available codes cover the spectrum of advective flow, advection-dispersion, heat, & chemical trans-
Heat transport	▪ Simulates flow where density-induced & other flow variations resulting from fluid temperatures differences invalidate conventional flow & chemical transport modeling. Used primarily in modeling of radioactive waste
Multi-phase flow	▪ Simulates movement of immiscible fluids (water & non-aqueous phase liquids) in either the vadose or saturated zones. Used primarily where

from EPA, 1991

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