This equation, when solved for the calculated fixed radius, r, becomes

$$r = \sqrt{\frac{Qt}{\pi \theta b}} \tag{7-10}$$

where

r = calculated fixed radius of the contributing area or zone, (L)
Q = well discharge rate, (L^3/T)
b = effective thickness of the production zone or saturated thickness of the aquifer, (L)
θ = effective porosity of the aquifer, (dimensionless)
t = time-of-travel, (T).

7.4.2.1 Solved Design Example 2

Calculated Fixed Radius: Consider the situation of a municipal well in Las Cruces, NM, which is located in a confined aquifer. The well pumps steadily at the rate of 5,450 m^3/day (1,000 gal./min), and the length of the well screen, which is equal to the saturated thickness of the aquifer is $b = 122$ m. Available literature sources cite the aquifer effective porosity as $\theta = 0.4$. Choosing a travel time of 10 years, determine the radius of the WHPA for the well under consideration.

Solution Substituting the values of the parameters into Eq (7-10) results in the determination of the calculated fixed radius as

$$r = \sqrt{\frac{(5,450\ \text{m/d})(10\ \text{y})(365\ \text{d/y})}{(\pi)(0.4)(122\ \text{m})}} = 360\ \text{m}$$

The 360 m (1,180 ft) calculated fixed radius is close to the arbitrary fixed radius of 303 m (1,000 ft) established by the New Mexico Environmental Department. However, if the period of protection is changed to 20 years, which is the typical life expectancy of a water-supply well in the area, the calculated radius will be 509 m, which is much larger than the arbitrary fixed radius of 303 m.

There are several limitations associated with Eq. (7-10), one being the assumption of a constant pumping rate, which is contrary to the practice of intermittent pumping in the real world. However, if the pumping rate in the example is taken as the average discharge rate for the period of calculation (10 years), then the calculated fixed radius would be reasonable. Another limitation is the fixed thickness of the production zone, which would change due to pumping if the aquifer is unconfined. In this case, the actual thickness of the production zone would be smaller than the initial saturated zone, resulting in underestimation of the ZOC. Eq. (7-10) also assumes that the length of the screen is equal to the thickness of the production zone, which may or may not be true. In cases where the length of screen is less than the saturated thickness of the aquifer, the length of the screen can be used as effective saturated thickness for a conservative estimation of WHPA radius.

7.4.3 Standardized Variable Shapes

The standardized variable shapes method uses analytical models to produce standardized shapes of the WHPA using representative hydrological criteria, time-of-travel, and hydrogeological boundaries. Various standardized shapes are calculated for different sets of hydrological conditions. Of course, various shapes of the WHPA are possible for each given set of conditions; however, this methodology uses quite a few generalized forms. Therefore, the most suitable form is chosen for each well by determining how closely that form matches the hydrogeological and pumping conditions of the well. Once the appropriate standardized form is determined, the so-called form can be oriented around the wellhead by aligning the shape in a manner that parallels the direction of flow of groundwater.

Once the shape is oriented, the upgradient portion of the WHPA is extended either to the flow boundary or to a specified time-of-travel boundary (Fig. 7-2). The upgradient extension of the WHPA can be determined using the time-of-travel equation (Fabian and Summers 1991).

The advantages of using the standardized variable shapes method are that this method requires little actual field data and can be implemented easily once the forms are calculated. Also, this method provides a more realistic delineation of the WHPA than either the arbitrary fixed radius or the calculated fixed radius method with only a minor increase in cost.

Again, once the standardized variable shapes are developed, the necessary, required information includes the pumping rate of the well, type of aquifer material, and direction of groundwater flow. The disadvantages of the method include the potential for introducing inaccuracies in the determination of WHPA with variable hydrogeological conditions.

7.4.4 Analytical Methods

The WHPA can be determined using analytical methods based on equations that describe groundwater flow and contaminant transport phenomena. For example, equations, such as those listed by Todd and Mays (2004), are based on the concept of uniform groundwater flow and are used to define the ZOC to a pumping well in a sloping water table (Fig. 7-3). Site-specific hydrogeologic data are required as input and include

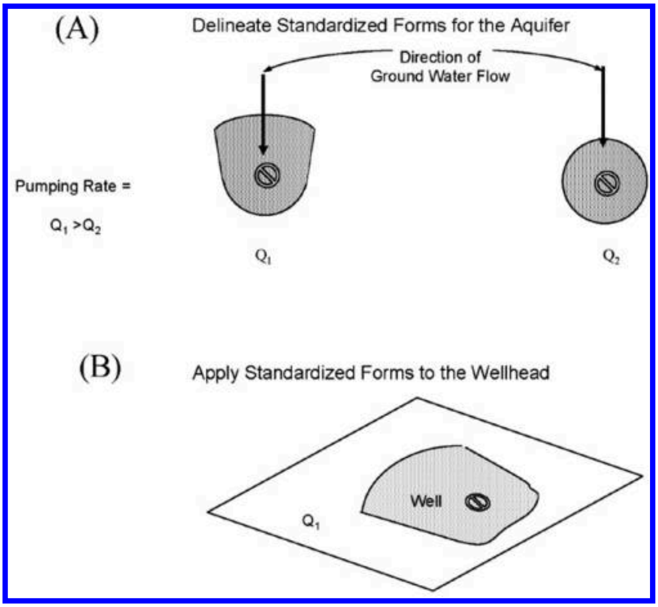

Fig. 7-2. Delineation of (A) standardized variable shapes, and (B) their application to wells of similar pumping rates and hydrological parameters

hydraulic conductivity, transmissivity, hydraulic gradient, pumping rate, and saturated zone thickness. Once this information is obtained, the following equations can be used to define the WHPA for a specific well as follows. The downgradient divide, X_L, is calculated from Eq. (7-11) as

$$X_L = -\frac{Q}{2\pi Kbi} \tag{7-11}$$

where

Q = pumping rate, (L^3/T)
K = hydraulic conductivity, (L/T)
b = length of the screened interval of the well or saturated thickness, (L)
i = hydraulic gradient of groundwater (L/L).

The limit of the flow boundary in y-direction, Y_L, is defined as

$$Y_L = \pm\frac{Q}{2Kbi} \tag{7-12}$$

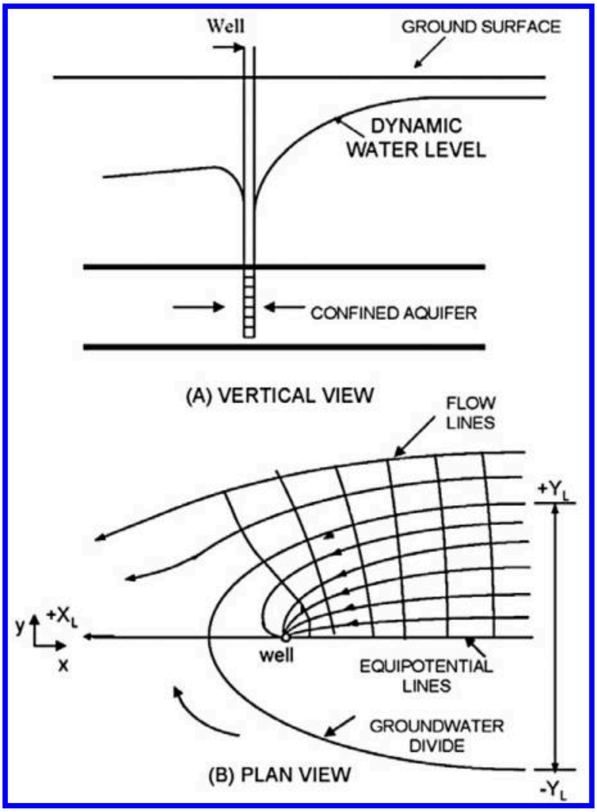

Fig. 7-3. Views of a water well completed in a confined aquifer; (A) Vertical view shows the ground surface elevation, piezometric surface, confined aquifer, well casing, and well screen; (B) Plan view indicates a partial flow net of streamlines and equipotential lines, pumping well, limits of ground water entering well, and groundwater divide

and the flow boundary defining the ZOC is given (EPA 1987) by

$$\frac{y}{x} = -\tan\left(\frac{y}{-X_L}\right) \tag{7-13}$$

Eqs. (7-11) through (7-13) define the ZOC around a well, but the upgradient boundary of the ZOC can extend a very large distance. To avoid such an unrealistic upgradient boundary, the EPA (1987) introduced an approach to calculate the upgradient boundary using the time-of-travel. Time-of-travel is estimated for the aquifer using the concept of the pore velocity equation. The pore velocity depends on the regional groundwater gradient and the local gradient at the vicinity of the pumping well. The distance, s, traveled during the time-of-travel, t, is calculated from the following equation:

$$s = v_r t + v_p t \tag{7-14}$$

where

s = distance the groundwater would travel in time, t, (L)
t = time-of-travel, (T)
v_r = regional groundwater velocity, (L/T)
v_p = velocity in the vicinity of the pumping well, (L/T).

On the basis of these equations, the menu-driven computer model called T-O-T was developed by Fabian and Summers (1991) to calculate the WHPA for a single pumping well. The model uses an iterative algorithm to calculate time-of-travel. The program uses the EPA-recommended criteria and methods to delineate WHPA, assuming ideal uniform conditions.

7.4.4.1 Solved Design Example 3 Consider the same aquifer as was described previously in Section 7.4.2.1, Solved Design Example 2, with $Q = 5{,}450\ \mathrm{m^3/d}$, $K = 5.45\ \mathrm{m/d}$, $b = 121\ \mathrm{m}$, and $i = -0.003$. Determine the downstream extension of the WHPA, X_L, and the maximum half width of the flow zone, Y_L.

Solution Using Eqs. (7-11) and (7-12), the downstream extension of the WHPA, X_L, and the maximum half width of the flow zone, Y_L, can be calculated as

$$X_L = -\frac{5{,}450\ \mathrm{m^3/d}}{2\pi(5.45\ \mathrm{m/d})(122\ \mathrm{m})(-0.003)} = 435\ \mathrm{m}$$

$$Y_L = \pm\frac{5{,}450\ \mathrm{m^3/d}}{2(5.45\ \mathrm{m/d})(122\ \mathrm{m})(-0.003)} = \pm 1{,}366\ \mathrm{m}$$

7.4.5 Hydrogeologic Mapping

This method uses geologic, geophysical, and dye tracing techniques to map flow boundaries and time-of-travel criteria. To determine flow boundaries, geological studies of the aquifer are undertaken to characterize the rock for the purpose of identifying permeable or impermeable boundaries. Geophysical investigations are used to determine the thickness and extent of unconfined aquifers. The groundwater hydrologic divide can be used to define the flow boundaries as well. Of course, hydrologic divides can be determined by mapping groundwater contours.

Moreover, this method can be used to delineate the WHPA for karst formations. Hydrogeologic mapping is well suited to conditions dominated by near-surface boundaries, which are found in glacial and alluvial aquifers with high pore velocities. Besides, it is suitable for highly anisotropic aquifers, such as fractured rocks and conduit flow in karst formations.

This delineation technique requires expertise in geological sciences and ability to make judgments on what constitutes flow boundaries. This method may prove expensive if hydrologic information is limited and direct field investigation becomes necessary.

7.4.6 Numerical Flow/Transport Models

Analytical methods are based on several assumptions. These assumptions include homogeneous and isotropic formations, two-dimensional flow, and simplified boundary conditions. Analytical methods also ignore the effect of temporal variation of pumping rates and other hydrological features, which may have significant effect on the shape and extent of the WHPA. For example, the arbitrary fixed radius method defines the WHPA by drawing an arbitrary circle around a well. The radius of the circle may depend on various factors, such as distance to the nearest source of contaminant and the number of years of desired protection. The cost, as well as the level of protection and its legal and environmental implication, determines the method that is used to delineate the WHPA and the input parameters used in each method. The most accurate delineation of WHPA is only possible through numerical modeling of groundwater flow and contaminant transport. Numerical modeling is the most expensive and time-consuming method. The accuracy of the modeling depends on the availability and accuracy of detailed hydrologic and geologic data. Numerical methods do make it possible to account for complex geologic and hydrologic boundaries, heterogeneous characteristics of the water bearing formation, and temporal variation of the pumping rates. Another important feature of the numerical models is the ability to simulate groundwater flow and contaminant transport in a three-dimensional domain.

Groundwater flow in the vicinity of a well may or may not be two-dimensional, depending on the geological characteristic of the aquifer and the well geometry. In addition to the assumption of two-dimensional flow in the first four methods, other assumptions include homogeneous and isotropic aquifer, infinitely extended boundaries, and fully penetrated and fully screened wells. These assumptions may overestimate the extent of the WHPA and, thus, increase cost without the benefit of increased protection. Conversely, the simplified methods may underestimate the extent of the WHPA and thus reduce the level of protection. Ramanarayanan et al. (1992) demonstrate that analytical methods underestimate the WHPA in comparison to numerical models, the latter of which better account for hydrologic features and temporal variation of pumping rates.

Several computer models have been developed to simulate the groundwater flow and contaminant transport. MODFLOW (McDonald and Harbaugh 1988), developed and maintained by the U.S. Geological Survey, can be used to simulate groundwater flow in a three-dimensional domain. MODFLOW can be coupled with other models, such as MT3D (Zheng 1993) or PATH3D (Zheng 1991), to simulate the contaminant transport around a single or multiple wells. Whereas MT3D can account for advection, dispersion, and chemical reaction of the contaminant, PATH3D accounts only for advection, thus resulting in a conservative estimate of the WHPA. Models such as MT3D can be used to develop contingency plans in case of a contaminant spill within the WHPA.

7.5 A CASE STUDY

Ten water-supply wells installed by the City of Las Cruces in the southern part of New Mexico were chosen for this case study. The City of Las Cruces WHP program was comprised of three phases:

1. Wellhead delineation,
2. Field assessment and contaminant inventory, and
3. Implementation.

7.5.1 Wellhead Delineation

The following describes the process of developing a wellhead protection program for the City of Las Cruces in southern New Mexico. The pumping rates from the wells ranged from 5,450 m^3/day (1,000 gal./min.) to 11,000 m^3/day (2,016 gal./min.). WHPAs were delineated for 10- and 20-year times-of-travel for the sake of comparison. The WHPAs for the 10 wells were delineated using the simplified EPA (1987) method. These results were compared with those obtained from more detailed three-dimensional interpretation of wellhead protection using a combination of a MODFLOW (McDonald and Harbaugh 1988) groundwater flow model and a PATH3D (Zheng 1991) particle-tracking model.

7.5.1.1 Hydrologic Models Both MODFLOW (McDonald and Harbaugh 1988) and PATH3D (Zheng 1991) were used to define the

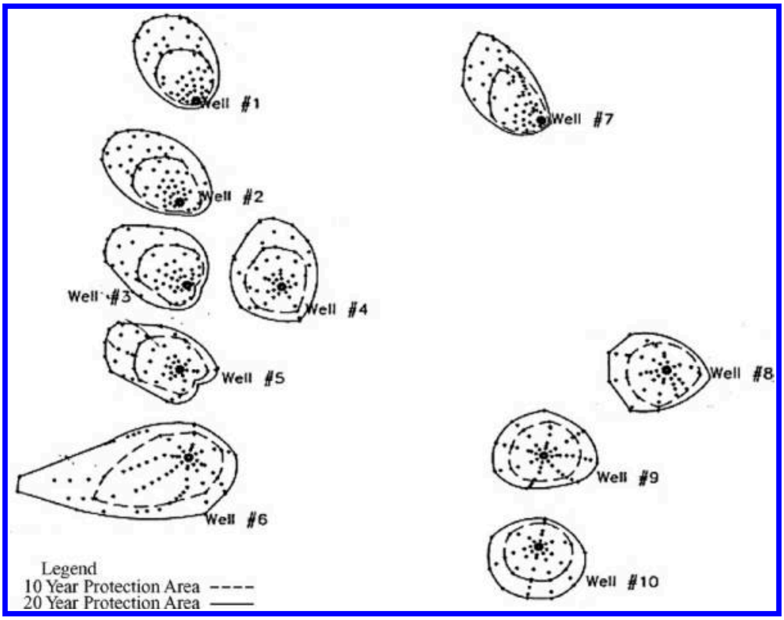

Fig. 7-4. Wellhead protection areas for 10 wells supplying the City of Las Cruces, New Mexico

10- and 20-year WHPAs around the 10 water-supply wells for the City of Las Cruces. These wells are located in the unconfined aquifer of the East Mesa formation. The water table in the aquifer is located at 120 m below the ground surface. The bedrock, or so-called bottom of the aquifer, is located at 300 m below the ground surface. The delineated areas were defined by backward tracing of particles placed in the wells for specified periods.

Fig. 7-4 shows the resulting two-dimensional views of the WHPAs produced by numerical modeling. The configuration of the delineated WHPA around each well depends on the hydrologic and geologic parameters surrounding the well. Using an arbitrary circle of 30 m (1,000 ft) around each well closely approximates the extreme boundaries of the 10-year protection zone in all the wells with the exception of Well No. 6 in which the pumping rate was higher than the average. From a practical point of view, however, protecting odd-shaped areas (such as those shown in Fig. 7-1) is difficult using circles alone, and the use of other shapes (such as rectangles or squares) might be necessary, because they better represent the delineated WHPA and conform to the land use planning in the area.

Theoretically speaking, the WHPAs presented in Fig. 7-4 represent 10 years and 20 years of protection, respectively. In reality, however, particles may reach the well sooner due to the presence of hydrologic or geological boundaries. For example, the delineated 20-year WHPA around Well No. 7 in Fig. 7-4 corresponds to a 20-year particle travel time on the northwest direction and only a 2-year travel time on the southeast direction. This is due to the presence of a geologic boundary in the southeast direction, which results in a shorter travel time. In this case, it is impossible to define a 20-year protection area around this well because of variable hydrogeologic characteristics surrounding the well. But a 2-year WHPA is possible and can be defined quite conveniently. In the case of Well No. 7, the protection area corresponding to shorter travel time implies a higher protection requirement in one side of the delineation zone compared to the other side, thus resulting in different economic and environmental implications, which would require more monitoring and priority given to the area corresponding to shorter travel time.

7.5.1.2 Vertical Contaminant Transport An important factor, which is often ignored in determining WHPA, is the potential for vertical transport of contaminants. The vertical hydraulic gradient is considerably smaller than horizontal gradient. This implies that defining the WHPA on the basis of horizontal contaminant transport alone will overestimate the extent of the WHPA significantly, resulting in costly overprotection of the well. This is especially true where the well screen is below the water table. Fig. 7-5 shows horizontal and vertical cross sections of a numerically-simulated contaminant plume for a well in the City of Las Cruces. In Fig. 7-5, the contaminant has traveled 1,300 m horizontally within 20 years while it has traveled only 3 m vertically within the same period. In this well the screen is 100 m below the water table, thus requiring a long time for the contaminant to reach the screen. The scenario could be different if the well were fully screened and subject to contamination introduced at the water table. Fig. 7-5 shows also that even within the same well, the magnitudes of horizontal and vertical contaminant transport vary depending on direction.

Fig. 7-5 shows not only the importance of vertical transport analysis but also the effect of well configuration on the economic and environmental implications of the WHPA. In general, the configuration of WHPA depends on duration of protection, hydrogeological characteristics of the aquifer, and well design and configuration. Well design can have a significant effect on the protection of a water well. Fig. 7-6 shows a water-supply well for the City of Las Cruces. The well is drilled in a two-layer aquifer where a 250 ft (76 m) unconfined upper aquifer is underlain by a confined lower aquifer. The well is screened partially, only in the lower aquifer. Further, the upper aquifer is separated from the lower aquifer by a clay aquitard. In this case, the clay layer effectively prevents the transport of any surface-borne contaminant from reaching the well screen, even if the contaminant were to be introduced within the WHPA. The initial

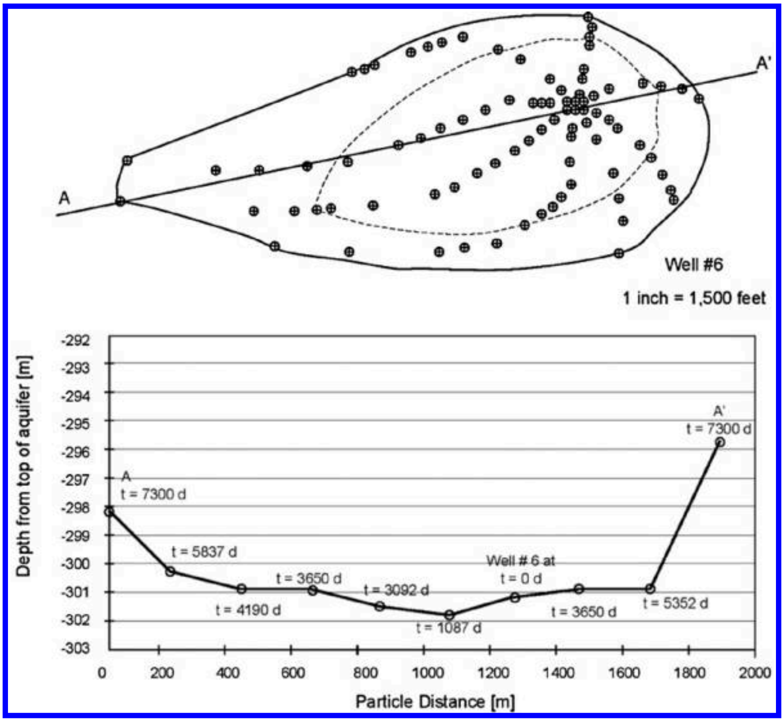

Fig. 7-5. Comparison of horizontal and vertical contaminant transport for correct delineation of the WHPA

borehole is grouted to prevent short circuiting, and there is an additional hydraulic buffer zone of 240 ft (73 m) above the screen. A WHPA defined for this under any of the aforementioned methods would be overly conservative.

7.5.1.3 Comparison with Analytical Method WHPA is a modular, semi-analytical groundwater flow model recommended by the EPA (1987) to generate wellhead protection areas. This model was used to generate the 20-year protection area for Well No. 6, and its results were compared with the wellhead protection zone defined using PATH3D (Fig. 7-7). The first noticeable difference is the shape of each wellhead protection area. The WHPA model produces a more uniform shape due to the homogeneity assumption of the model. The PATH3D results shows a larger and more realistic shape taking into account the hydrogeological variability around the well. The numerical models generally result in a more realistic delineation of the WHPA; however, within a given hydrologic model, the results may vary depending on the input parameters. For example, large