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REVIEW OF U.S. EPA-RECOMMENDED AND GERMAN WELLHEAD PROTECTION AREA DELINEATION METHODS

R. O. Strobl International Institute for Geo-Information Science and Earth Observation
Water Resources Department, Enschede, The Netherlands
P. D. Robillard World Water Watch, Cambridge, Massachusetts, U.S.A.

The surface and subsurface area around wells that is delineated with the sole purpose of protecting water supplies from potential contamination is known as a wellhead protection area (WHPA). Federal regulations, however, do not require private water systems, such as those mainly found in agricultural settings, to identify such activity-restricted areas around wellheads. Ironically, private well operators, even though typically limited by financial resources, often have considerable control over regulating and excluding certain land use activities in the vicinity of their water supply. The WHPA delineation methods, as recommended by the U.S. Environmental Protection Agency (EPA), vary widely, providing more accurate delineation results directly proportional to the cost of the method. Several well-established German WHPA delineation approaches, on the other hand, are relatively inexpensive and simple in application, and may, therefore, provide a reasonable alternative for private water system operators to ensure safe drinking water. To provide a basis for a comparative analysis, the U.S. EPA-recommended and German WHPA delineation methods are presented and examined with respect to their validity, suitability, and differences. In addition, several German models for aquifer regeneration and restoration are presented.

INTRODUCTION

In the United States, almost half of the population relies on drinking water from community or private wells. In rural areas, almost 95% of the water used for domestic purposes is groundwater. The reliance on groundwater to meet drinking water demands is continuously growing, while the public has grown increasingly aware of potential groundwater contamination problems (Bouwer, 1990; EPA, 1989; Panasewich, 1985). Careless management of contaminant sources can cause degradation of groundwater supplies (Guiger and Franz, 1991). One solution to this problem is to define areas of protection around wells and springs which are likely to be impacted by contaminants and to limit or control land use within these areas. Such protected areas are referred to as wellhead protection areas (WHPAs) (EPA, 1987). A WHPA is defined as "the surface and subsurface area surrounding a water well or wellfield, supplying a public water system through which contaminants are reasonably likely to move toward and reach such a water well or wellfield (United States, 1986)." This definition of a WHPA, however, fails to include and protect recharge areas which contribute groundwater to private water systems. Nonetheless, private water system operators, particularly farm operators, often have greater control of regulating and restricting land uses in the recharge areas of their water supply (Doscher, 1992).

On the other hand, many of the European wellhead protection programs, such as the German program, include private water systems in agricultural settings. While U.S. WHPA delineation methods include arbitrary, analytical, mapping, as well as numerical techniques, German delineation WHPA methods for demarcating the equivalent WHPA (i.e., zone II) consist of analytical, iterative, and graphical techniques. Only in recent years have German environmental agencies employed numerical methods, mainly to accurately accommodate hydrogeologically complex field conditions. In addition, WHPA delineation in Germany generally takes the restoration process of groundwater moving through the aquifer into consideration. The main objective of this paper is to examine the validity, suitability, and differences of current U.S. WHPA methods with respect to established German WHPA methods and approaches.

WHPA DELINEATION IN THE UNITED STATES

In Europe, groundwater protection programs were evident in the last century and have, hence, inspired the fairly recent United States' progress in the delineation of WHPAs (Cleary and Cleary, 1991). Cleary and Cleary (1991) gave a brief overview of the European approach to the delineation of WHPAs particularly focused on the success of the German and Dutch wellhead protection programs. In light of the European success, the EPA (1987) described the primary approaches to WHPA delineation in this country. Six different methods for WHPA delineation were presented. Hansen (1991) compared five of the six different WHPA delineation methods (not variable shapes) for municipal wells near Wichita, Kansas. As expected, the numerical methods were concluded to be the most accurate, but were only a viable alternative for large municipalities or individuals with the necessary resources, due to their extensive input data and specialized training requirements. Guiger and Franz (1991) described the development of a WHPA delineation computer program using numerical methods and applied it to the delineation of a WHPA for a municipal well in Littleton, Massachusetts. Horsley (1983), delineated the WHPAs for municipal wellfields on Cape Cod, Massachusetts with analytical equations derived using aquifer transmissivity and storativity as well as pumping rate and period as inputs to compute a fixed radius about the well. By extending the area to the upgradient groundwater divide, the zone of contribution was delineated. Ramanarayanan et al. (1992) compared the results of an analytical model with those of a numerical model for delineating WHPAs and concluded that the analytical model underestimated the WHPA due to temporal variations of pumping rates and other hydrologic features.

The only literature found describing the implementation of WHPAs for private water supplies in agricultural settings was by Doscher (1992). In this study, wellhead protection delineation methods for farmsteads primarily suffering from chemical contamination due to fertilizers and other related agricultural chemicals were evaluated. Four of the six types of wellhead protection delineation methods, namely the arbitrary fixed radius, calculated fixed radius, analytical models, and numerical flow and transport models, as identified by the EPA (1987), were applied to four farmsteads in Lancaster County, Pennsylvania. However, using only secondary data, the application of the four methods for delineating WHPAs in those rural environments was a rather uncertain and difficult task.

WHPA DELINEATION IN GERMANY

Since the 1930's, German groundwater protection programs have attempted to assure adequate protection of the natural high quality and quantity of groundwater. German groundwater protection is founded on a time-distance integrated protection zone concept. As such, there generally exists the possibility to delineate up to four wellhead protection zones in the recharge area of a drinking water well. In general, wellhead protection zones are subdivided into zones I, II, and III. If the recharge area extends more than 2 km, zone III is broken down into zone IIIA, which extends to a non-scientifically based distance of 2 km, and into zone IIIB, which extends beyond this distance of 2 km and demarcates the drainage boundaries of the well (Cleary and Cleary, 1991). The purpose of zone III is to protect against distant polluting sources, especially against nondegradable or hard to decompose chemical and radioactive substances. The purpose of zone II, on the other hand, is to protect against microbial pollution and other contamination that stem from a variety of human activities and sources which are in the proximity to the well bore. Some of the banned activities and installations include storage of organic fertilizers, roads, pit latrines, camping grounds, and cemeteries. The application of organic fertilizers, however, is considered harmless to the groundwater if a soil layer of organic and fine organic components of more than two meters is located above the water table (Mull, 1981). The outermost boundary of zone II is defined as the 50-days line, which is a flow path by which groundwater takes about 50 days to reach the well area. Also, the covering layers of the aquifer in question are usually taken into consideration in zone II. In rare cases, zone II is divided into zones IIA, defined by a 10-days line, and IIB, defined by a 50-days line. Finally, the purpose of zone I is to protect the immediate surroundings of the well against point sources. The boundaries of protection zone I are to be at least 10 m from the well. However, there is a stipulation that zone I should be extensive enough so that organic manuring can be permitted in zone II. To guarantee the groundwater quality in zone I, it is obligatory for municipal waterworks to purchase all the land within this zone and deny the public access to it. As a rule of thumb, the prohibition and restriction of certain activities in water protection areas increases from zone to zone when approaching the drinking water well (Umweltbundesamt, 1985; Bolsenkötter et al., 1984; Mull, 1981).

The 50-days line was developed in the 1930's under the assumption that the spread of disease, such as through pathogenic bacteria and viruses, via drinking water supplies could be eliminated in that time period. This space/time concept came about from the realization that in order to deplete or minimize polluting sources that have different degrees of persistency, the seepage and flow paths have to vary appropriately (Schleyer et al., 1992). It has, however, been practice by German authorities not to solely consider a 50-days line as a basis for zone II, especially if high apparent flow velocities are existent that make the protection areas computationally unrealistic and extensive, or even lead to protection zones that go beyond the drainage area boundaries. This is the case for most karst and many joint aquifer systems (Bolsenkötter et al., 1984).

It is important to note that the German groundwater protection program normally considers that the natural cleansing action of an aquifer can generally be estimated from the unsaturated upper confining layers as well as from the conditions in the aquifer itself. Depending on the depth to the piezometric surface, the type, thickness, and extent of the covering layers may be considered when delineating the protection zones. This regeneration and restoration process involves several chemical, physical, and biological processes. To be on the safe side, the cleansing action of the covering layers is only taken into consideration if the depth to the piezometric surface (in the case of a phreatic water table, at its highest level) exceeds 4 m. Despite these factors, some microbials are particularly persistent and have persistence rates of up to 250 days. This fact would make a 50-days line insufficient in terms of epidemiological protection of groundwater in all aquifers that lack good sorption conditions, such as aquifers in widely fractured rock or karst aquifers (Schleyer et al., 1992). However, in humid areas of moderate climate, the maximal lifetime of bacteria will not surpass 60 days in subsoil. German investigations indicate a maximal bacterial lifetime of 50 days for such regions (Matthess, 1990; Mull, 1981).

EPA-SUGGESTED WHPA DELINEATION METHODS

EPA (1987) suggests six primary methods for delineating a WHPA, which vary in sophistication as well as in cost, amount and diversity of required geologic and hydrologic data, and time of implementation. These methods are described briefly in order of increasing technical complexity and cost (EPA, 1987; Cleary and Cleary, 1991).

1. *Arbitrary Fixed Radius (AFR) Method*: This method involves drawing a circle of a specified radius around the well(s) being protected. The radius is either set arbitrarily or estimated from generalized hydrogeologic assumptions. This method has some advantages in that it is relatively economical and requires little technical knowledge. The disadvantages are that it embodies a high degree of uncertainty, especially in anisotropic, heterogeneous media, such as a karst aquifer, and may over- or underprotect the WHPA. It may be appropriate for microbial or physical threats, or possibly as a temporary WHPA in the preliminary stages of WHPA delineation for chemical contamination problems.

2. *Calculated Fixed Radius (CFR) Method*: This approach involves drawing a circle around a well based on a designated time of travel (TOT) criterion. The time corresponds to anticipated dilution or dispersion of the pollutant before it reaches a well. Similar to the AFR method, it also does not incorporate anisotropy, heterogeneity, and a sloping potentiometric surface.

3. *Simplified Variable Shape (SVS) Method*: This technique uses standardized forms, obtained by analytical methods, with flow boundaries or TOT used as criteria. Shapes are selected to fit the approximate conditions encountered at wellheads, wellfields, or springs of concern. Site conditions should resemble the hydrogeologic trends considered when establishing the standardized forms. The advantages of this method are that it can be implemented with ease once the shapes of standardized forms have been developed and also that only a minimum amount of field data is needed. The disadvantages, on the other hand, include that the approach may not be accurate in areas with numerous geologic heterogeneities and hydrologic boundaries, or if the flow directions near a well vary from those derived from regional assessments.

4. *Analytical Modeling Methods*: These methods solve simplified flow/transport partial differential equations, representing simplified aquifer conditions, analytically by computer simulation of idealized initial and boundary conditions. They are the most commonly used methods and are often used when greater precision is desired. The advantages of these methods are that they are normally easily understood and solved, and consider some important site-specific hydrogeologic parameters. The disadvantage is that these methods do not consider aquifer heterogeneities, hydrologic boundaries, and nonuniform evapotranspiration or precipitation.

5. *Hydrogeologic Mapping Methods*: These techniques map flow boundaries and TOT using geophysical, geomorphic, and geological data, age assessment, and dye-tracing methods. They can be used to delineate WHPAs in karst systems and noncarbonate fractured bedrock aquifers. In addition, they are quite useful when delineating WHPAs in small aquifers of glacial or alluvial origin. The main disadvantage of these methods is that specialized expertise in geologic and geomorphic mapping, and significant judgment as to what constitutes a flow boundary is essential. Moreover, it may be inappropriate when delineating WHPAs for deep or large aquifers.

6. *Numerical Modeling Methods*: These methods are similar to analytical modeling methods, but are capable of handling complicated boundary and hydrogeologic conditions, such as heterogeneous geology. Groundwater flow and contaminant transport equations are used that consider a multitude of hydrogeologic and contaminant conditions, and, therefore, potentially make these the most accurate methods. The advantages of these methods are that they have an extremely high potential degree of accuracy and can be used for delineating nearly all possible types of hydrogeologic settings. Furthermore, numerical models can be used dynamically to reproduce changing conditions in a WHPA. The disadvantages are that they are relatively costly and require considerable technical expertise.

GERMAN WHPA DELINEATION METHODS

In most cases, methods for calculating the 50-days line for zone II (the approximate equivalent of a standard WHPA in the U.S.) rest on simple equations and rules. There are also various graphical and iterative techniques available for this purpose. It is suggested by Hofmann and Lillich (1973) that when delineating zone II, at least two methods be used to compare the delineation results. In addition, it is suggested that typically all sides of the WHPA be buffered with a certain safety margin to account for heterogeneities and other uncertainties. The following section introduces some of these methods with some relevant discussion and sample calculations where available.

Methods suggested for delineating the 50-days line (zone II)

1. Method by Wyssling (1979)

This method allows for the direct calculation of the transit time (flow time) of groundwater from a desired point on the flow axis to a pumping well. To apply this method, the aquifer is assumed homogeneous and the pumping rate small in relation to the discharge rate of groundwater flow. In addition, only the central axis of flow is taken into account. The transit time to a well is calculated as follows. H, k, I, p, and Q are assumed to be known values:

H = aquifer thickness, m

k = hydraulic conductivity of the aquifer, m/s

i = hydraulic gradient for $Q = 0$

p = effective porosity

Q = pumping rate of the well, m^3/s

The quantities of the flow field that need to be calculated are:

$$B = \frac{Q}{H*k*i} = 2b \quad , \quad x_0 = \frac{B}{2\pi} = \frac{Q}{2\pi * H * k * i} \quad , \quad and \quad v_0 = \frac{k*i*86400}{p} \tag{1}$$

where B is the upgradient width of contribution in meters due to the pumping rate, b is the width of contribution at the pumping well in meters, x_0 is the distance from the pumping well to the downgradient boundary of the zone of contribution in meters, and v_0 is the apparent groundwater flow velocity in meters/day.

Once the above quantities have been calculated, then the approximate values of the upper and lower zone II boundaries, s_u and s_l, can be computed (see Figure 1) via:

$$s_{u/l} = \frac{\pm d + \sqrt{d(d+8x_0)}}{2} \tag{2}$$

where s_u and s_l are the upgradient and downgradient distance (meters), respectively, from the pumping well to a point on the flow axis with the desired time of travel and $d = v_0 \times t$, where t is the desired time of travel (v_0 in m/day, t in days).

To compute the exact values for t:

$$t = \frac{x - x_0 * \ln(1 + \frac{x}{x_0})}{v_0} \tag{3}$$

where t is the time of travel from a point P_x on the flow axis to the pumping well in days and x is the distance from a point P_x to the pumping well (x is a positive quantity upgradient and a negative quantity downgradient of the pumping well) in meters.

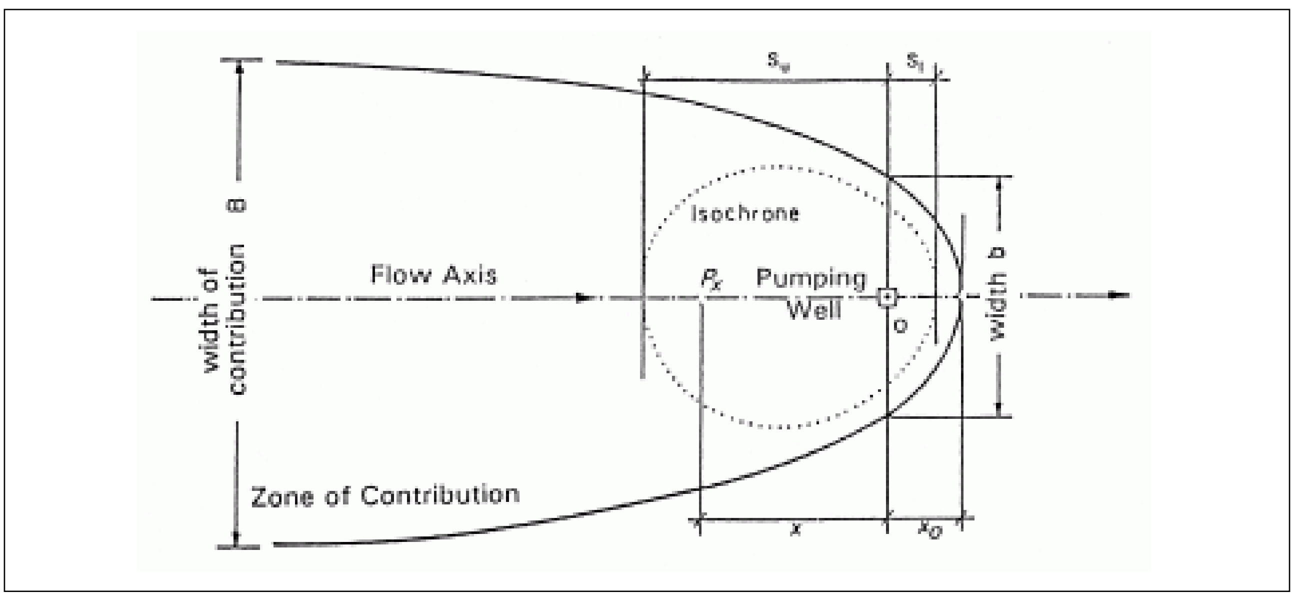

Figure 1. Graphic representation of a flow system at a pumping well (Eqs. (4) and (5); Wyssling, 1979.

With these calculated quantities and consideration of the flow direction, the corresponding zone of contribution due to a specific pumping rate can be delineated (Figure 1). As long as the protection zone is delineated using an isochrone, then it is possible to compute the distances, s_u and s_l ,on the flow axis corresponding to a desired time of travel using Equation 2 as a first approximation. This typically leads to useful results in the upgradient direction, while in the downgradient direction, especially with large v_0, s_l can become larger than x_0. Hence, s_l extends beyond the zone of contribution, which is not possible. It is, therefore, recommended to verify the distances, s_u and s_1 ,with the help of Equation 3 and then to adjust these distances to reflect known flow boundaries. Equation 3 is particularly suitable for the direct calculation of the time of travel from any desired point P_x on the flow axis (such as a contaminant source or a road, for example) to the pumping well. In this way, it is possible to reach one's goal solely by using Equation 3 and a trial-and-error method.

In the case of very small to negligible v_0, v_0 tends to 0 and x_0 tends to ∞. The calculation of t using Equation 3 becomes impossible. In this case, the following equations are used (terms defined in Equation 1):

$$t = \frac{x^2 \pi * H * p}{Q * 86400} \qquad and \qquad x = \sqrt{\frac{t * Q * 86400}{\pi * H * p}} \tag{4}$$

which give the time of travel and the radius x, respectively, for purely centripetal flow for an operating pumping well.

2. Method by Hofmann and Lillich (1973)

This method involves the calculation of the 50-days line using an iterative method and is especially useful in cases where limited hydrologic data are available. Strictly speaking, the use of this iterative method is only valid for homogeneous aquifers or wells that completely penetrate an aquifer. Moreover, this approach is based on the numeric derivation of the dynamic hydraulic gradient at each point on the drawdown curve. The shape of the drawdown near a well can be approximated for confined and phreatic aquifers (Equations 5a and b, respectively; Todd, 1980:

$$h - h_w = (h_0 - h_w)\frac{\ln(r / r_w)}{\ln(r_0 / r_w)} \tag{5a}$$

$$(h - h_w)^2 = (h_0 - h_w)^2 \frac{\ln(r / r_w)}{\ln(r_0 / r_w)} \tag{5b}$$

where h is the elevation of the lowered piezometric surface above a datum plane in meters, r is the distance from the center of the pumping well in meters, h_w is the elevation of the dynamic piezometric surface in the pumping well from a datum plane in meters, h_0 is the elevation of the pre-pumping (original) piezometric surface above a datum plane in meters, r_0 is the horizontal distance from the center of the pumping well to the beginning of the drawdown in meters, and r_w is the radius of the pumping well in meters.

Due to the functional correlation between the distance r from the well and the elevation h of the drawdown curve, it is possible to compute the average dynamic hydraulic gradient from a point to the well, using, for instance, Equation 5a. The distance to the 50-days line (E_{50}) is given by:

$$E_{50} = v_a (m / \sec) * 50 * 86400(\sec) \tag{6}$$

Hence, E_{50} is directly proportional to the apparent groundwater flow velocity, which, in turn, is directly proportional to the average dynamic hydraulic gradient. It is, thus, the objective to find through optimization, the distance from a well, by which the dynamic hydraulic gradient just reaches a certain value, which when used for calculating the apparent groundwater flow velocity, produces the same distance for the 50-days line.

3. Method by Spitz et al. (1980)

The method presented by Spitz et al. (1980) is a simple analytical method for delineating the 50-days line and allows for convective calculations for single wells without any mathematical simplifications. In contrast to other methods, it does not require time-consuming graphical constructions. Strictly speaking, however, this method is only applicable to aquifers with a constant horizontal hydraulic conductivity and a constant aquifer thickness. The influence of dispersion effects are incorporated into the computations by a dispersivity factor, which is the ratio of the 50-day distance including dispersion to the 50-day distance excluding dispersion.

The longitudinal and lateral dispersion coefficients, D_L and D_T, are approximated as:

$$D_L = \alpha_L v_a \qquad and \qquad D_T = \alpha_T v_a \tag{7}$$

The mixing width of contamination can generally be described as a characteristic length of a Gaussian distribution by two to three deviations (Spitz et al., 1080). Spitz et al. (1980) assumed that the mixing width is described by three standard deviations. The mixing width is dependent on the longitudinal dispersivity, α_L , the average flow distance, x_0, and the velocity distribution along the flow path. The standard deviation, a , and therefore, also the mixing width, b, that occurs after a minimum residence time, t_m (i.e., 50 days), can be easily calculated for parallel flow with a constant apparent groundwater flow velocity, v_a.

With an average flow distance of:

$$x_0 = v_a t_m \tag{8}$$

the mixing width, b, is given as:

$$b = 3\sigma = 3\sqrt{2\alpha_L x_0} = 3\sqrt{2\alpha_L v_a t_m} \tag{9}$$

The dispersivity factor, γ, gives a first assessment of the amount of dispersion for the case when the pumping rate is much smaller than the groundwater flow rate and is given by:

$$\gamma = \frac{x_s}{x_0} = \frac{x_0 + b}{x_0} = 1 + \frac{3(2\alpha_L)^{0.5}}{(v_a t_m)^{0.5}} \tag{10}$$

Case 1: Delineation of the 50-days line for an aquifer with negligible groundwater flow

With a negligible groundwater flow in an aquifer, the pumping of a well produces radially symmetrical flow lines, which are dependent on the pumping rate, Q, the aquifer thickness, m, and the effective porosity, n_e. Neglecting dispersion, the average residence time to the well is $t = t_m$ and the 50-days line is a concentric circle around the pumping well. The circle's radius, x_0, also known as the "convective radius", is computed from the so-called cylindrical formula:

$$x_0 = \left(\frac{Qt}{\pi \; mn_e} \right)^{0.5} \tag{11}$$

Case 2: Delineation of the 50-days line for an aquifer with an observed groundwater flow

In this case, the flow field and therefore the average residence times are dependent on the pumping rate, Q, the effective porosity, n_e, the aquifer thickness, m, in addition to Darcy's velocity, v_0. The flow field is described by the following relations:

Stream function:

$$\Psi = \frac{Q}{2\pi\ m(x^2 + y^2)^{0.5}} \cos\beta \tag{12}$$

Velocity:

$$v_x = v_0 + \frac{Q}{2\pi\ m(x^2 + y^2)^{0.5}} \cos\beta \qquad and \qquad v_y = \frac{Q}{2\pi\ m(x^2 + y^2)^{0.5}} \tag{13}$$

where x and y define the coordinates parallel and perpendicular, respectively, to the flow direction and β = arc tan (y/x). The upper portion of Figure 2 depicts the flow field for this case.

In order to calculate the average residence times in a universally applicable manner, the above equations are solved in a dimensionless form as follows:

$$x^* = \frac{2\pi v_0 m}{Q} x \qquad and \qquad y^* = \frac{2\pi v_0 m}{Q} y \tag{14}$$

$$t^* = \frac{2\pi v_0^2 m}{Q n_e} t \qquad and \qquad \alpha_L^* = \frac{2\pi v_0 m}{Q} \alpha_L \tag{15}$$

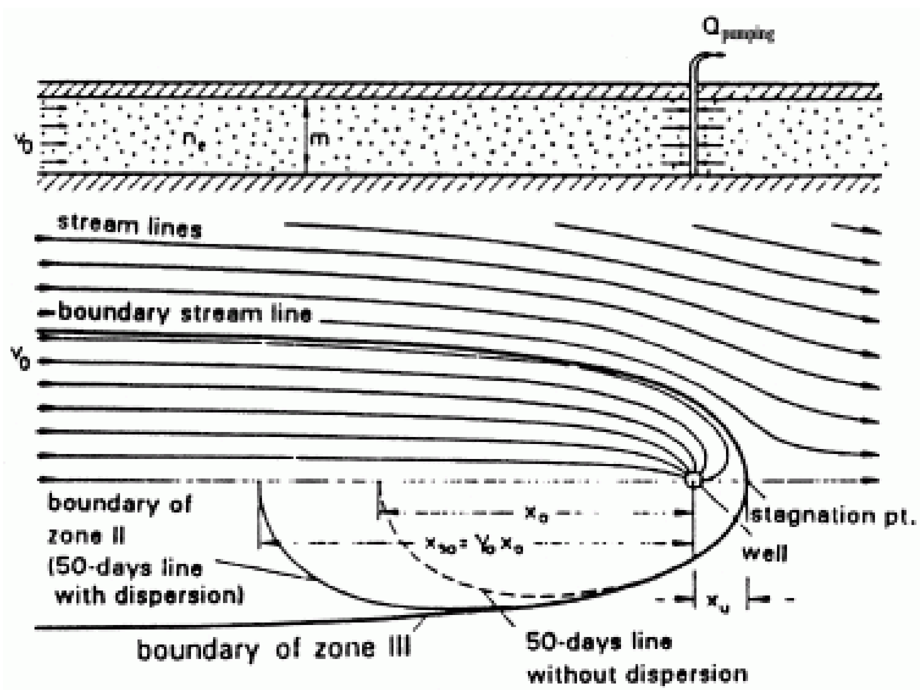

Figure 2. Delineation of the 50-days line for an aquifer with an observed groundwater flow (Spitz et al., 1980).

where x^* is the dimensionless form of the coordinate parallel to the flow direction and y^* is the dimensionless form of the coordinate perpendicular to the flow direction.

The dimensionless average residence time, which is obtained by neglecting dispersion, is calculated as follows:

$$t^* = y^* * \cot\beta + \ln\left(\frac{\sin\beta}{\sin(y^* + \beta)}\right) \tag{16}$$

To compute the residence times along the *x*-axis, Equation 16 simplifies to:

$$t^* = x^* - \ln(x^* + 1) \tag{17}$$

Figure 3 depicts the results of Equations 16 and 17.

The upper portion of Figure 3 illustrates the average residence times along the x-axis (Equation 17), while the lower portion of Figure 3 shows the results from Equation 16. Figure 3 shows that the 50-days line is an elliptical-like line if dispersion is neglected. This line intersects the x^*-axis at two points, whose "convective distances" upgradient (x_0^*) and downgradient (x_u^*) to the pumping well represent the conventional zone II borders (i.e., without dispersion effects).

To evaluate the influence of dispersion, the lateral dispersion may be neglected for practical purposes. The influence of dispersion can, thus, be analytically evaluated by the mixing width for

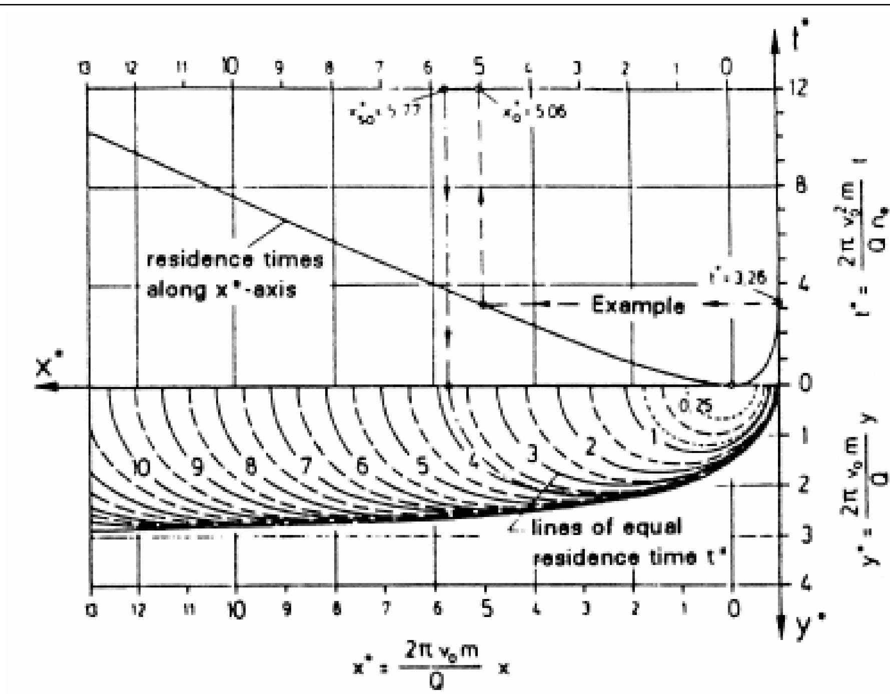

Figure 3. Dimensionless residence times for an aquifer with observed flow (Spitz et al., 1980).

a contaminant which is introduced into the aquifer along the x-axis. Figure 4 shows the dispersivity factor, g , versus the convective distances, x_0^* and x_u^*, and the longitudinal dispersivity, α_L^*.

By multiplying the convective distances x_0^* and x_u^* with the respective dispersivity factors, the main dimensions of zone II, namely x_{S0}^* and x_{Su}^*, can be computed, and the influence of

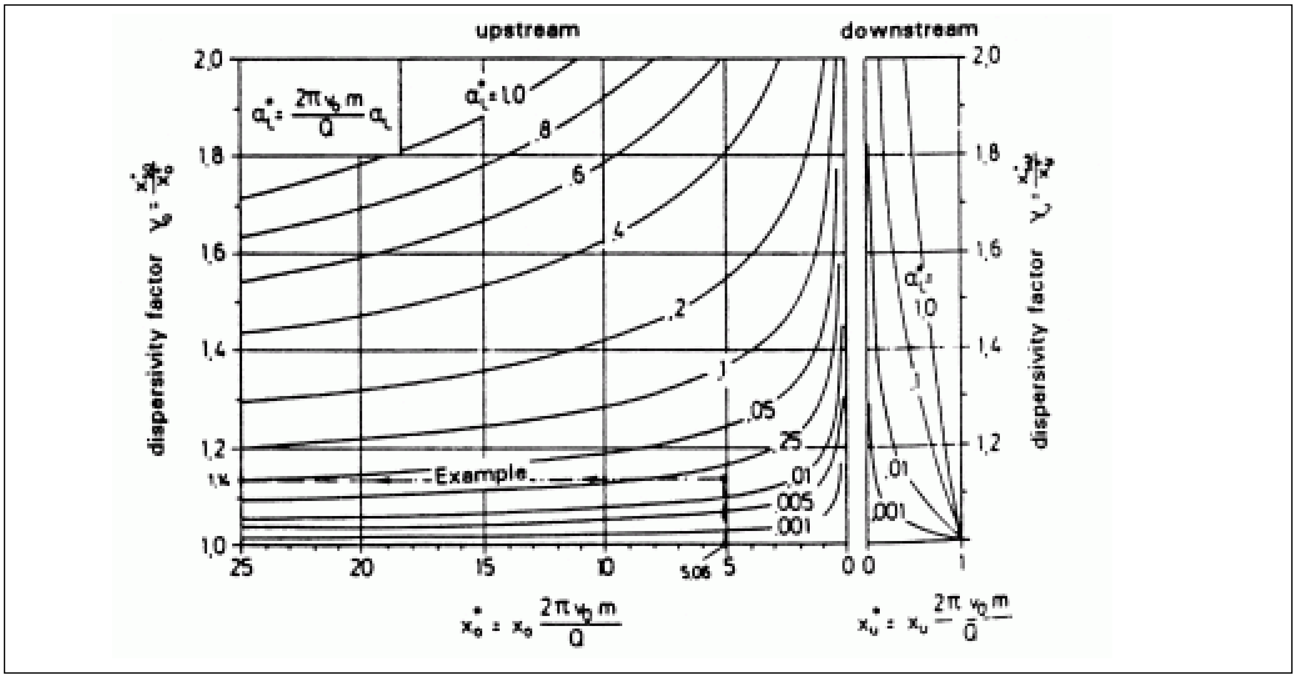

Figure 4. Dispersivity factor for an aquifer with an observed flow (Spitz et al., 1980).

dispersion is included. In order to define the total contour of zone II, one may assume that the "zone II shape" is approximately similar to the shape found by using a line of equal average residence time, which runs through both determined x_S^* points. This can be accomplished by using Figure 3 with interpolation between two lines of equal average residence time.

4. Method by Mull (1981)

This method consists of three approaches for delineating zone II. One approach is an experimental as well as theoretical method that uses the results of several tracer tests. If these tracer test results are not available, then Mull (1981) recommends the application of one of the other two techniques. For practical purposes, the reader is referred to Mull (1981) for a detailed description of the experimental/theoretical approach using tracer tests. The two remaining alternative methods are described below.

(a) *Assuming radial flow to a well*

When the assumption of radial flow to a well is made, a circle around the well defines the 50-days line. If it is further assumed that ideal conditions (i.e., isotropy and homogeneity) of the aquifer, and confined flow exist, then the average velocity v_a is related to the average travel time t by:

$$\frac{dr}{dt} \quad v_a \quad \frac{k_f}{n_c}\frac{dh}{dr} \tag{18}$$

where (dh/dr) is the hydraulic gradient, k_f is the permeability (m/s), h is the potential head (m), n_e is the effective porosity, and r is the distance from the center of the pumping well (m).

From the relation:

$$\frac{dr}{dt} \quad \frac{Q_d}{2 \quad k_f m}\frac{1}{r} \tag{19}$$

where v_a is the medium tracer velocity (m/s), Q_d is the discharge (m^3/s), m is the aquifer thickness (m), r_0 is the radius of the well (m), and r_{50} is the radius of the 50-days line (m). For the case where $r_0 << r_{50}$:

$$r_{50} = \left(\frac{Q_d t_{50}}{\pi \; m n_e} \right)^{0.5} \tag{21}$$

(b) *Assuming a well in uniform flow field*

If the assumption of a well in a uniform flow field can be made, dimensionless units are employed according to Spitz et al. (1980):

$$t^* = \frac{2\pi \; v_{f0}^2 m}{Q_d n_{em}} t \qquad \textit{and} \qquad x^* = \frac{2\pi \; v_{f0} m}{Q_d} x \tag{22}$$

where v_{f0} is defined as the specific discharge of the uniform flow. When considering the problem as two-dimensional, t^* is as follows:

$$t^* = y^* \cot(\arctan(\frac{y}{x})) + \ln \left(\frac{\sin(\arctan(\frac{y}{x}))}{\sin(y^* + (\arctan(\frac{y}{x})))} \right) \tag{23}$$

However, if only two points on the x-axis are desired, t^* becomes:

$$t^* = x^* - \ln(x^* + 1) \tag{24}$$

Figure 5 depicts the graphical representation of Equation 24.

For two points on the y-axis, written in dimensionless form:

$$y^* = (2t^*)^{0.5} \tag{25}$$

Figure 6 shows the four points of the 50-days line obtained from Equations 24 and 25.

In order to define the zone II contour, graphical interpolation is used.

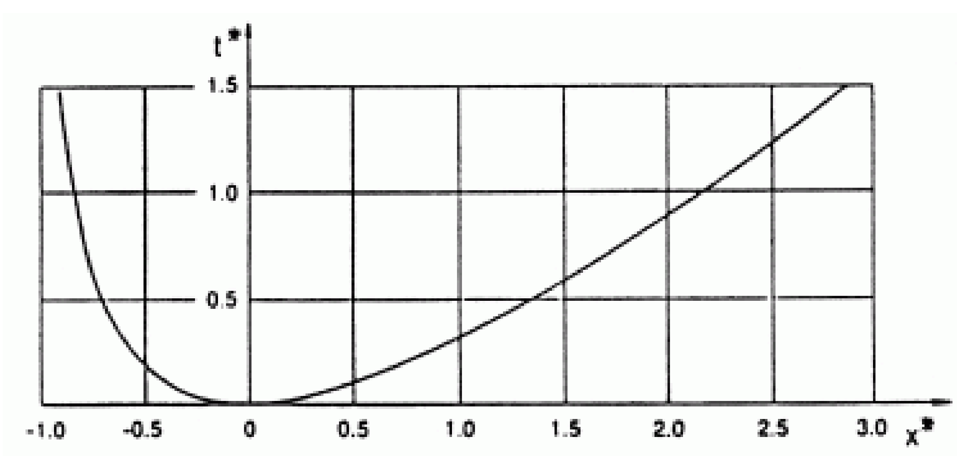

Figure 5. Graphical representation of Equation 24 (Mull, 1981).

5. Method by Nahrgang (1965)

This method can be used to plot the zone II boundary only if the flow field is sufficiently known. Nevertheless, this method is particularly useful if there are multiple wells and if the region in question is characterized by different hydraulic conductivities. The theoretical basis for this method is Darcy's law. A major disadvantage of this approach is, on the other hand, that quite involved and tedious graphical constructions are necessary, involving examination of preferably a large number of known streamlines to determine multiple points along the 50-days line. The reader is, thus, directed to Nahrgang (1965) for a detailed description of the technique via an elegant example.

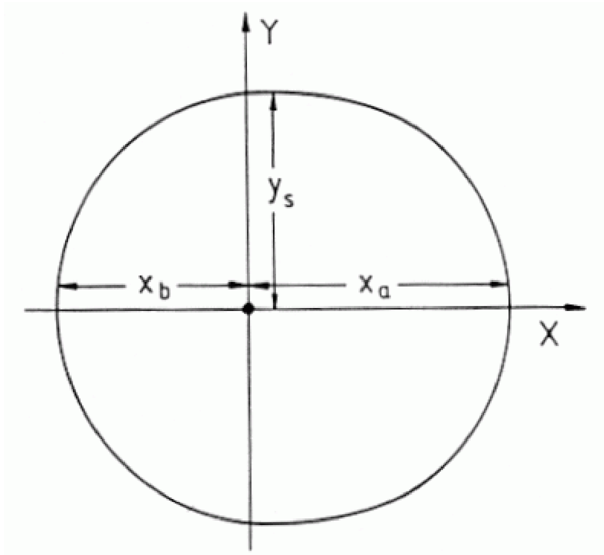

Figure 6. Four points of the 50-days line (Mull, 1981).

Methods suggested for accounting for the regeneration capabilities of the aquifer

1. Method by Rehse (1977)

Rehse (1977) presented an empirical method to incorporate a purification index of the covering layers of an aquifer. The method estimates the degradation and elimination of organic waste substances, pathogenic bacteria, and viruses in porous sediments.

To use this method, the following considerations and steps are required:

(1) The first 4 m of the covering layers are ignored for safety reasons.

(2) For the underlying covering layers in the unsaturated zone, the cleansing index I of the individual covering layers is obtained from the upper portion of Table 1, where M is the material number found in Table 1, M9 to M12 are selected materials usually found in the unsaturated zone, H is the sufficient covering layer thickness for bacteriological elimination and regeneration, and I is the index for dimensioning, equal to $1/H$.

(3) The degree for cleansing, M_d , for the covering layers is calculated as follows:

$$M_d=h_1*I_1+h_2*I_2+h_3*I_3+... \qquad (26)$$

where h_1, h_2, h_3, ... are the thicknesses of the sectioned covering layers (m). For an adequate cleansing, M_d must be greater or equal to 1.0. An adequate cleansing corresponds to a cleansing

Table 1. Indices for Dimensioning (Rehse, 1977)

M	Material Description	H (m)	I=1/H
1	Humus, mean biological condition, 5-10% humus, %-10% clay	1.2	0.8
2	Clay without fissures, clayey silt; high clayey silt	2.0	0.5
3	Clayey silt to silt	2.5	0.4
4	Silt; silty sand; Sand with little silt and clay	30-4.5	0.33-0.22
5	Clean fine to medium sand	6.0	0.17
6	Clean medium and coarse sand	10.0	0.1
7	Clean coarse sand	15.0	0.07
8	Silty gravel, rich in sand and clay	8.0	0.13
9	Light silty gravel, rich in sand	12.0	0.08
10	Clean fine to medium gravel, rich in sand	25.0	0.04
11	Clean medium to coarse gravel, rich in sand	35.0	0.03
12	Stones, little gravel and sand	50.0	0.02
	***** Water Table *****		
		L (m)	I=1/L
9	Light silty gravel, rich in sand	a 100 b 150 c 170 d 200	0.01 0.007 0.006 0.005
10	Clean fine to medium gravel, rich in sand	a 150 b 200 c 220 d 250	0.007 0.005 0.0045 0.004
11	Clean medium tocoarse gravel, rich in sand	a 200 b 250 c 270 d 300	0.005 0.004 0.0037 0.0033
12	Stones, little gravel and sand	a 300 b 340 c 360 d 400	0.0033 0.0029 0.0028 0.0025

in groundwater after a residence time of 50 days. From a theoretical standpoint, the protection zone II is not needed in such a case.

(4) The required remaining residence time, T, in days, in the groundwater is calculated from the following equation:

$$T=50(1-M_d) \tag{27}$$

2. Method by Bolsenkötter et al. (1984)

Bolsenkötter et al. (1984) demonstrated an empirical method similar to Rehse's (1977) method for handling the cleansing action of fissured (fractured) covering layers. The cleansing action of the fissured covering layers should be considered when dealing with jointed aquifers if the delineation of zone II by the known or estimated apparent groundwater flow velocities alone would lead to a likely exaggeration of that zone. Moreover, the cleansing action is dependent on the amount of ion exchange as well as ion, bacteria, or virus adsorption to fine matter (clay, silt) or minerals (mica, chlorite, zeolite, etc.).

Vertical seepage often only brings about minor cleansing for larger fracture widths and high infiltration rates. Consequently, the cleansing action for horizontal flow within the aquifer is greater. Therefore, the fissured covering layers should be given a maximum attainable degree of cleansing of $M_d = 0.5$ (i.e., $I = 0.5/H$), so that even with local highly fissured conditions, an additional cleansing with the combined horizontal flow can still be maintained. Table 2 lists the indices for dimensioning the fissured covering layers.

The remaining horizontal expansion ($E_{\text{min.}}$) of zone II with a flow time of 25 days (extra area should be allotted when maximum cleansing through the covering layers is not achieved) can be computed via a cylindrical formula:

$$E_{\text{min.}} = R_{25} = \left(\frac{Q_{25}}{M * P_n * \pi} \right)^{0.5} \tag{28}$$

where

Table 2. Indices for Dimensioning of Fissured Covering Layers (Bolsenkötter et al., 1984)

Material	H (m)	I=0.5/H
Diabase, marly stone	10	0.05
Sandstone with interlaying claystone, clayslate and mica-schist,phyllite	20	0.025
Basalt and other vulcanites	30	0.017
Greywackes, arkoses, silty and clayey bound sandstone	50	0.01
granite, granodiorite, diorite, syenite	70	0.007
quartzite, highly flintysandstone, flinty slate	100	0.005
marble, pure limestone	200	0.0025

Q_{25} = pumping rate, runoff for springs, in m^3 in 25 days

M = depth to the water table in m

P_n = estimated effective porosity of the aquifer

If a severe, above average jointing exists, then the cleansing index I for the next worse cleansing layer (i.e., beneath the jointing) should be utilized. If a fissured covering layer is additionally overlain by loose material, then the cleansing action of this loose material, as described by Rehse (1977), can be considered. As in Rehse's (1977) method, the entire zone II, however, must have a minimum depth of 4 m to the water table.

3. Method by Renner (1972)

Renner (1972) proposed a method to obtain the residence time of water in the unsaturated zone. In essence, this method considers the cleansing capabilities of the unsaturated zone. However, similar to Rehse's (1977) method, it ignores the root zone because often this zone is permeated with many holes and tunnels from small animals as well as broken up by dead roots. Such conditions would make it possible for contaminants to be practically washed through this zone without renovation. In addition, the capillary fringe is ignored due to locally changing water contents and a changing infiltration direction (from vertical to horizontal). This method is only applicable to aquifers where the unsaturated zone is made up of porous material. To use this method, two necessary assumptions must be made:

(1) The infiltrating water is direct precipitation only (i.e., not water from springs, residential runoff, etc.), should be evenly distributed, and should immediately infiltrate the soil.

(2) Homogeneous soil must be assumed with no large holes or pores.

For the use of this mostly graphical method, the reader is referred to Renner (1972).

CONCLUSIONS

While there has been only a minimum attempt towards delineating WHPAs in agricultural settings, the delineation of such areas in municipal environments has received an appreciable amount of attention. One reason for this might be that the resources available to a municipal community may permit more extensive hydrogeologic investigations of the aquifers in question than could possibly be expected from private agricultural operations (Doscher, 1992). Depending on financial and other resources available in an agricultural operation, Doscher (1992) determined that at least one of the six methods for delineating a WHPA as identified and recommended by the EPA (1987) can be used in an agricultural setting. Ultimately, the selection of an appropriate WHPA delineation method will be contingent on the requirements and resources of the implementor. In addition, with appropriate delineation, private water systems in agricultural settings can be virtually regarded as safe as municipal water systems.

After a brief look at the six EPA-recommended methods, this paper took a close look at some well-established German wellhead protection methods and approaches that include private water systems of agricultural settings. Table 3 summarizes the possible applications, advantages, and disadvantages of all the methods examined.

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Table 3. Summary of All Examined Methods

	Likely Applications	Advantages	Disadvantages
Arbitrary Fixed Radius Method	May be appropriate for microbial or physical threats; temporary WHPA	Relatively economical; little technical expertise required	Cannot handle heterogeneous and anisotropic media
Calculated Fixed Radius Method	Essentially homogeneous and isotropic media	Relatively economical; includes a TOT	Cannot handle heterogeneous and anisotropic media
Simplified Variable Shape Method	Applicable to areas similar to areas for which standardized forms have been developed	Implemented easily once standardized forms are developed	Not accurate for areas with numerous geologic heterogeneities
Analytical Modeling Methods	Useful in near-homogeneous conditions	Easily solved; includes some site-specific hydrogeologic parameters	Does not consider heterogeneities and nonuniform precipitation
Hydrogeologic Mapping Methods	Useful in small aquifers of glacial or alluvial origin	Can handle karst systems	Requires specialized expertise; inappropriate for deep or large aquifers
Numerical Modeling Methods	Useful in nearly all types of hydrogeologic settings	Can handle complex hydrogeologic conditions; accurate	Expensive; requires technical expertise
Wyssling (1979) Method	Useful when the direction of flow is essentially a straight line	Easily computed	Cannot handle heterogeneous and anisotropic media
Hofmann and Lillich (1973) Method	Wells that completely penetrate the aquifer	Little hydrological data required	Cannot handle heterogeneous media
Spitz et al. (1980) Method	Cases when dispersion may be significant	Convective calculations without any mathematical simplifications	Knowledge of longitudinal dispersivity of media required
Mull (1981) Method	Cases where tracer test results are available	Convective calculations without any mathematical simplifications	Uniform or radial flow must be assumed
Nahrgang (1965) Method	Cases where region is characterized by a wide range of hydraulic conductivities	Useful if multiple wells are present	Excessive graphical constructions necessary
Rehse (1977) Method	Cases where the overlying soil horizons can be expected to renovate infiltrating water	Simple calculation procedures	Knowledge of depth of unsaturated zone
Bolsenkötter et al. (1984) Method	Fractured overlying soil horizons	Simple calculation procedures	Knowledge of depth of unsaturated zone
Renner (1972) Method	Cases where the overlying soil horizons can be expected to renovate infiltrating water	Relatively easy to use if data available	Some graphical construction; field data of soil properties needed

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ADDRESS FOR CORRESPONDENCE
R.O. Strobl
ITC
Hengelosestraat 99
P.O. Box 6
7500 AA Enschede
The Netherlands

E-mail:strobl@itc.nl