2 Step 2: Delineating the Wellhead Protection Area

Introduction: what this step is about

This step involves making an inventory of all Public Water Supply (PWS) wells included under the plan and gathering basic information about each well. The most important part of this step is to **identify the area that must be managed to reduce the likelihood of contamination of your well** — the Wellhead Protection Area (WHPA). Simply stated, the WHPA is the part of the landscape — above or below ground — that contributes water that will eventually reach the pumping well. If a contaminant reaches ground water within the well system's contribution area, the contaminant can move with the ground water into the well. If the contributing area for the well is identified and management strategies set in place to manage certain activities, the possibility that the well might become contaminated can be significantly reduced. This is the area where your wellhead protection (WHP) plan will apply.

WHPA delineation identifies the land area that must be managed to reduce the likelihood of contamination of your well.

In the first part of this step, you will compile basic data for each well in your water system.

By the end of this step, you will have a sound, defensible idea of what land area needs to be managed to protect the quality of your water supply and a map showing each well location with a WHPA delineated around each well or group of wells.

Ground-water primer

Ground water is water moving through the cracks and pore spaces in underground rock formations called *aquifers*. Aquifers are ground-water reservoirs that store and transmit water. It is the discharge from aquifers that keep rivers flowing long after the rain has stopped. Aquifers may be divided into two categories, unconfined and confined. An unconfined aquifer is one in which water only partially fills the aquifer. The upper surface of the zone of saturation, known as the water table, is free to rise and fall. The surficial aquifer is the unconfined aquifer that immediately underlies the land surface. A confined aquifer is completely filled with water and is overlain by a low permeability confining layer which restricts the movement of water into and out of the aquifer.

Under natural conditions, aquifers are filled or *recharged* by precipitation falling on the land surface and percolating downward to the ground water. Water leaves or *discharges* from the aquifer in areas such as springs, streams, or rivers. Ground water moves continuously from areas of natural recharge to areas of natural discharge. However, unlike rivers, ground-water movement is very slow, typically from less than an inch to just a few feet each day. The rate of movement of ground water depends, in part, on the effective permeability of the aquifer material, which in turn depends on its porosity – the size and connectedness of the cracks and pore channels in the aquifer material.

Wells are simply holes drilled into an aquifer through which water may be removed. Pumping water from a well causes the water level in the well to fall below the water level in the surrounding aquifer. This causes water in the aquifer to flow toward and into the well to replace the water being pumped out. For an unconfined aquifer, the land area surrounding a well in which precipitation infiltrates to the ground water and eventually flows to the pumping well is known as the *contributing area* for the well. Within the contributing area, any contaminant released to the environment that reaches the ground water can reasonably be expected to move toward and possibly reach the well. Therefore, in situations where the surficial, unconfined aquifer is used for water supply, the WHPA should at least encompass the contributing area around your well. This would include wells located in the Piedmont and Mountain areas of the State and wells withdrawing water from the surficial aquifers of the Coastal Plain area.

The size of the contributing area for a well is controlled by the rate at which water is pumped from the well and the rate at which the aquifer receives recharge. For example, if an aquifer in a particular area had an average recharge rate of 500,000 gallons per day per square mile, a well pumping one million gallons per day would have a contributing area of two square miles. If this same aquifer had an average recharge rate of 100,000 gallons per day per square mile, then, the size of the contributing area for a well pumping one million gallons per day would be 10 square miles. That is, for a given pumping rate, the smaller the average recharge rate for the aquifer, the larger the contributing area has to be to supply the water.

The average recharge rate to the confined aquifers of the coastal plain are, in general, small in comparison to the average recharge rate to the surficial, unconfined aquifers. WHPAs for wells withdrawing water from these aquifers could potentially be unmanageably large if based on the size of the contributing area. Also, because the contributing area for a confined aquifer may be located many miles from the well, accurate determination and management of WHPAs bases on contributing areas present numerous technical and jurisdictional difficulties. As a result, WHPAs for wells withdrawing water from confined coastal plain aquifers are often based on a time of travel calculation. A time of travel calculation uses the rate of ground-water movement to estimate how long water or a contaminant will take to reach a well from a point within the aquifer. This approach has been adopted in many states for defining WHPAs for confined aquifers. In North Carolina, the WHPA for wells withdrawing water from certain confined aquifers encompasses the area surrounding the well for which the time of travel from the outer edge of the area to the well is 10 years. A ten-year period was selected to provide time to assess the potential impact of any ground-water contamination discovered within the WHPA and for developing appropriate remediation and ground-water protection strategies for the water supply. A WHPA based on a longer time of travel may provide a greater degree of protection to the well and allow more advance warning to respond to a contamination incident within the WHPA, but it will also expand the area to manage under your WHP Plan.

Procedure: what you need to do to complete Step 2 toward your WHP plan

Gather information

Know your well system

Collect information on your well and its aquifer as a basis for WHPA delineation

Before you begin the actual delineation of the WHPA for a PWS well, you should obtain as much information as possible about the well. This information should be collected for all wells that compose your water system. Knowledge about your water system will help in the methods and calculations used to define a WHPA.

At a minimum, the information you compile should include:

1. Well owner/system name;
2. Well name/number;
3. Well location;
4. Date drilled;
5. Town or community served by well;
6. Source of supply (aquifer);
7. Well depth;
8. Well diameter;
9. Casing depth;
10. Top and bottom of screened or open hole section(s);
11. Pumping rate in gallons per minute;
12. Pumping period in minutes per day;
13. Well yield as determined from a 24-hour drawdown test (North Carolina Administrative Code 15A NCAC 18C.0402); and
14. Copy of 24-hour drawdown test.

This information may be recorded on the well-site evaluation form shown in Attachment 2. Most of the information you need should be readily available. Well construction records and well yield tests are required for all public water supply wells. Information on well depth, casing depth, well diameter, screen or open hole sections, and yield can be obtained from well construction records available from the NC DENR–Division of Water Quality–Groundwater Section or the well contractor that drilled the well.

Delineate the WHPA

You must use an acceptable method to delineate the WHPA. Methods accepted in North Carolina include:

- Calculated fixed radius
- Variable shape
- Ground-water velocity
- Aquifer source–volume

Methods for WHPA delineation accepted in North Carolina include:

- Calculated fixed radius
- Variable shape
- Ground-water velocity
- Aquifer source–volume

Other methods of WHPA delineation such as computer modeling or hydrogeologic mapping may be used if they can be shown to more accurately define the contributing area for the well. However, such methods require site-specific data and considerable technical expertise and are therefore more expensive to apply.

The first two methods listed above are suitable for delineating WHPAs for wells withdrawing water from unconfined aquifers. This includes all wells in the Piedmont and Mountains and wells withdrawing water from the surficial aquifer in the Coastal Plain. The last two methods listed above are suitable for wells withdrawing water from confined coastal plain aquifers (highly confined and certain semi-confined aquifers). Other more sophisticated delineation methods may be used to more accurately define the area contributing water to the well system, if data and expertise are available. The state will review and accept delineations based on such methods if the state concludes that the input data and results are of acceptable quality.

Calculated Fixed Radius. This method is the simplest of all acceptable methods for WHPA delineation. The method results in a WHPA that is a circle with the well at the center, and is applicable to all wells withdrawing from unconfined aquifers in the Coastal Plain and for all wells in the Piedmont and Mountain regions. The only information needed to apply this method is the **maximum permitted daily withdrawal** for the well and the **recharge rate** of the aquifer.

To calculate the area of the proposed WHPA, first calculate the contributing area by simply dividing maximum permitted daily withdrawal by recharge rate:

$$A=\frac{Q}{W} \qquad (1)$$

where:
A = contributing area, square miles
Q = maximum permitted daily withdrawal, gallons per day
W = average recharge rate, gallons per day per square mile

To account for directional differences in certain aquifer parameters, the contributing area calculated by equation 1 is doubled to define the WHPA. The radius around the well for the WHPA is obtained by:

$$r=4213\sqrt{\frac{Q}{W}} \qquad (2)$$

where:
r = radius from well of WHPA, feet
Q = maximum permitted daily withdrawal, gallons per day
W = average recharge rate, gallons per day per square mile
4213 = factor for converting area in square miles to radius in feet; includes doubling of the contributing area

The maximum permitted daily withdrawal is determined from information on well yield and an assumed daily period of well operation (in minutes per day). The well yield is the maximum sustained pumping rate possible for the well and is determined from a 24-hour pumping test required by state regulations for all PWS wells. The well yield (in gallons per minute) is multiplied by 720 (the number of minutes in 12 hours) to determine the maximum permitted daily withdrawal. A value of 720 is used because state regulations require that public supply wells provide the system's average daily demand in 12 hours pumping time. If the actual pumping time exceeds 12 hours, then the actual pumping period in minutes per day should be used in the calculation.

Information on average recharge rates will be derived from published information. Average recharge rates in North Carolina range from 150,000 to 600,000 gallons per day per square mile. Average recharge rates across the state are shown in the figure in Attachment 3 and are available from the North Carolina Public Water Supply Section.

Example of Fixed Radius Calculation

Well yield from a Piedmont well is 30 gallons per minute. Assuming a 12-hour pumping day, maximum permitted daily withdrawal (Q) is 21,600 gallons. Recharge rate is estimated to be 300,000 gallons per day per square mile. Using equation 1, the contributing area would be 0.072 square miles, or about 46 acres:

$$A = \frac{Q}{W} \qquad A = \frac{21{,}600}{300{,}000}$$

A = 0.072 sq. miles = 46 acres

Using equation 2, which accounts for doubling the contributing area, the radius of the WHPA would be 1,130 feet or ~0.21 miles:

$$r = 4213\sqrt{\frac{Q}{W}} = 4213\sqrt{\frac{21{,}600}{300{,}000}}$$

$r = 4213x0.2683$ = **1,130 feet**

Once the radius (r) is calculated, the resulting WHPA can be drawn on a map as a circle with the well in the center.

Variable shape. This method is more complicated than the calculated fixed radius method, but it can improve accuracy of the delineation substantially if the required information exists. Therefore, this method is preferred over the calculated fixed radius method by the State of North Carolina. The **size** of the contributing area is determined as before, but the **shape** of the area is determined from properties of the aquifer and the direction of ground-water flow in the area.

Size. As in the calculated fixed radius method, the contributing area is calculated from equation 1:

$$A = \frac{Q}{W}$$

where:
A = contributing area in square miles
Q = maximum permitted daily withdrawal in gallons per day
W = recharge rate in gallons per day per square mile

Unlike the calculated fixed radius method, the contributing area calculated with the equation above is not doubled to set the size of the WHPA.

Shape. After determining the size of the contributing area, the next step is to determine its shape and position relative to the pumping well. This is a much more complex problem because it may involve consideration of the direction of ground-water movement and the hydraulic gradient in the vicinity of the well, hydraulic boundaries, and directional transmissivity.

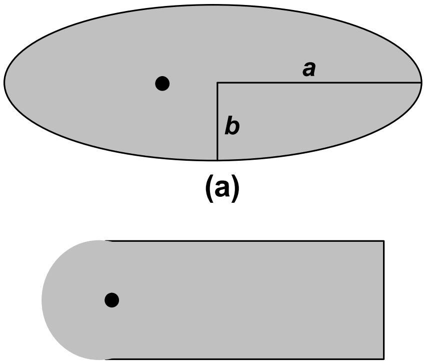
1. **Direction of ground-water movement and the hydraulic gradient.** For a well withdrawing from an unconfined aquifer that is not affected by either hydraulic boundaries or directional transmissivity, the shape of the contributing area is controlled primarily by the hydraulic gradient. The hydraulic gradient, or slope of the ground-water table in unconfined aquifers, can be determined from water level maps or from field measurements of water levels in different water wells. Where the water table is nearly flat, as near the water-table divide in broad interstream areas of low relief, it can be assumed that the contributing area and the associated WHPA will have a circular shape. Where hydraulic gradients are moderate, contributing areas are elliptical in shape and oriented in the direction of ground-water movement: the steeper the gradient, the more elongated the ellipse. In the absence of specific water-level data, it is generally assumed that the direction of ground-water movement past a well under natural, non-pumping conditions is parallel to the slope of the land surface.
2. **Directional differences in water-transmitting capacity, or directional transmissivity.** Under the simplifying assumptions employed in the Wellhead Protection Program, this factor applies only to the Piedmont and Mountains. The ground-water system in the Piedmont and Mountain area consists of a surficial layer of unconsolidated granular material referred to as regolith overlying consolidated bedrock. Ground water in the Piedmont and Mountains occurs both in the pore spaces between the rock particles comprising the regolith and in a network of interconnected fractures in the bedrock. As a result, the transmissivity is generally not the same in all directions but tends to be largest in the direction parallel to the dominant fracture set in the bedrock. These directional differences in transmissivity result in elliptical-shaped contributing areas around pumping wells. Where the transmissivity is twice as large in the direction of the dominant fracture set as at right angles to it, the contributing area will be an ellipse twice as long in the direction of the dominant set as at right angles to it. In some areas of the Piedmont and Mountains the transmissivity of the bedrock parallel to the dominant fracture set may be five or more times that at right angles to it which will result in a contributing-area ellipse with a length five or more times its width. However, for purposes of the Wellhead Protection Program, a 2:1 ratio of transmissivity is assumed in the absences of site-specific transmissivity data. This assumption results in an elliptical contributing area twice as long as it is wide.

3. **Hydraulic boundaries formed by streams or topographic divides.** Hydraulic boundaries refers to physical features that limit the extent of contributing areas. In the Piedmont and Mountains these are most commonly ridgelines and perennial streams, lakes, and reservoirs. Ridgelines commonly coincide with divides in the water table which, in hydraulic terms, are no-flow boundaries. Thus, in the Piedmont and Mountains, drawdowns produced by most pumping wells do not extend past adjoining ridgelines. Where contributing areas drawn around wells cross ridgelines, it may be necessary to move the boundary of the contributing area inward to the ridgelines. Whether it is necessary to move the boundary inward to the ridgeline depends on how far the boundary extends past the ridgeline. If it extends a maximum of a hundred or so feet beyond the ridgeline, no change in the boundary need be made because the water-table divide can be offset short distances. Where the contributing area boundary is moved inward to a ridgeline will result in a decrease in the size of the WHPA. To compensate for this reduction, it may be necessary to extend the WHPA boundaries up and down the valley, parallel to the ridgelines, to encompass the size calculated for the contributing area. Whether this extension is necessary depends on whether the contributing area intersects a perennial stream or other surface-water body. Water moving through ground-water systems ultimately discharges to streams or other surface-water bodies. Where drawdowns caused by pumping wells reach these streams or surface-water bodies, ground-water discharge may be reduced or stopped. Additionally, surface water may be induced to flow into the source aquifer. Where induced infiltration of surface water occurs, it results in a reduction in the size of the contributing area making it unnecessary to compensate for the decrease in the size along ridgelines by extending the contributing area, and therefore the WHPA, up and down the stream valley.

   In the Coastal Plain, topographic divides (“ridgelines”) between streams rarely, if ever, limit the extent of contributing areas. Therefore, the only hydraulic boundaries of any importance in the Coastal Plain are those formed by large perennial streams in direct hydraulic contact with the source aquifer. This condition is most likely to affect only the unconfined surficial aquifers and the semi-confined aquifers, where they are in direct contact with major streams.

Two basic WHPA shapes can result using this method. One of the shapes is an ellipse, the other is a combination of a semicircle and a rectangle. The decision to use one or the other is based upon the amount of information that is available and the specific hydrogeologic conditions. However, it is important to note that regardless of how WHPAs are drawn, due consideration should be given to hydraulic boundaries (i.e., surface-water bodies and ridgelines) that may modify the shape of the contributing area.

For Piedmont and Mountain locations, the shape of the elliptical area (a) is derived from the common assumption of a 2:1 ratio in directional transmissivity. This results in an ellipse that is twice as long in one direction as the other (see Figure 1a).



(a)

(b)

Figure 1. Basic shapes of wellhead protection areas derived from the simplified variable shape method: (a) ellipse and (b) semicircle and rectangle. Small solid circle represents pumping well.

Using this assumption, the equations for determining the lengths a, and b in Figure 1 are:

$$a = 4213\sqrt{\frac{Q}{W}} \qquad (3)$$

and

$$b = a/2 \qquad (4)$$

where Q and W are the same as in Equation 1 and *a* and *b* are in feet.

Example of Variable Shape Calculations

Yield from a Mountain well is 50 gallons per minute. Ratio of directional differences in transmissivity is 2:1. WHPA assumed to be elliptical with 2:1 axial ratio. Assuming a 12-hour pumping day, average pumping rate (Q) is 36,000 gallons per day. Recharge rate (W) is estimated to be 400,000 gallons per day per square mile. Using equations 3 and 4, the long axis (*a*) of an elliptical WHPA would be 1,264 feet; the short axis (*b*) would be 632 feet:

$$a = 4213\sqrt{\frac{36{,}000}{400{,}000}} = \textbf{1,264 feet}$$

b = *a*/2 = **632 feet**

The next step is to place the ellipse in the proper position with respect to the well. Two things need to be considered when doing this; the orientation of the ellipse or rotation (direction of the long axis "*a*") and how much the ellipse is shifted (how much closer the well is to one end of the ellipse than the other end. See Figure 1(a).

The ellipse will be oriented or rotated such that the long axis "a" is along the direction of the dominant fractures in the rock. Water flows more easily toward the well in this direction (transmissivity is greater). Since water moves more easily along this path, it will get to the well more quickly than water coming from other directions.

Direction of the dominant fractures can sometimes be obtained from geologic maps. A trained geologist may also be able to determine fracture directions from field observations.

The position of the well within the elliptical-shaped contributing area depends on the pumping rate of the well, the regional hydraulic gradient, and its position with respect to the water-table divide and recharging streams. If this information is known, several analytical techniques are available to calculate the distance from the pumping well to the downgradient edge of the contributing area.

If specific hydrogeologic information is available, the shape of the WHPA might look like Figure 1(b). A series of calculations are done to delineate the area. More than one attempt may be required to insure that the area matches the area calculated for the size of the contributing area as calculated in Equation 1.

For further information on application of the variable shape method, contact the North Carolina Rural Water Association, or consult the North Carolina Wellhead Protection Guidebook (NCDENR, 1995).

Special method for confined aquifers. In highly confined and certain areas of semi-confined aquifers, using rate of recharge (“W” in Equation 1) may result in calculating an unmanageably large WHPA. In such cases, two modified approaches to delineating the WHPA may be used.

Special methods may be used to estimate WHPAs in confined aquifers

Ground-water velocity. Many states base their WHPAs on ground-water *time of travel*. North Carolina uses a period of ten years, a period believed to be appropriate to provide an adequate time frame for assessing the impacts of any ground-water contamination discovered within the WHPA and for developing a remediation strategy.

For the ground-water velocity method, if hydraulic conductivity and hydraulic gradient are known, the ground-water velocity can be calculated and used to define the boundary of the area around the well within which the time of travel to the well is ten years. The equation used to calculate ground-water velocity is:

$$v = \frac{K}{n} x \frac{dh}{dl} \qquad (5)$$

where: v = velocity, feet per day
K = hydraulic conductivity, feet per day
n = porosity, dimensionless
dh/dl = the hydraulic gradient in foot vertical per foot horizontal

Of these factors, only porosity can be estimated with acceptable accuracy; other values must be derived from site-specific data.

Example of Ground-water Velocity Calculation

The following values have been measured in a confined aquifer in the Coastal Plain:

hydraulic conductivity (K) = 0.0003 feet per second = 26 feet per day
porosity (n) = 0.2
hydraulic gradient (dh/dl) = 5 feet in 1600 feet

Using equation 2.4:

$$v = \frac{K}{n} x \frac{dh}{dl} = \frac{26}{0.2} x \frac{5}{1600} = 130 \, x \, 0.0031 = 0.41 \text{ feet/day}$$

At a velocity of 0.41 feet/day, a circle defining a 10-year time of travel has a radius of:

0.41 feet/day *x* 365.25 days/year *x* 10 years = **1498 feet**

<u>Aquifer source–volume method</u>. The lack of specific data on hydraulic conductivity or hydraulic gradient will preclude determination of ground-water velocity for most WHPAs. In that case, it will be necessary to use a method that estimates the volume of aquifer from which water withdrawals are made. This is called the aquifer source-volume method. The volume of an aquifer that supplies withdrawals for a specified period of time can be estimated by the following equation:

$$V_P = Q\left(\frac{gal}{\min}\right) \times t_d\left(\frac{\min}{day}\right) \times \left(\frac{ft^3}{7.48\, gal}\right) \times \left(\frac{365.25\, days}{year}\right) \times \frac{P\,(years)}{n} \qquad (6)$$

where:
V_p = the volume of aquifer in cubic feet that supplies water for time P
Q = well yield in gallons per minute
t_d = the daily pumping period in minutes per day
P= the period of withdrawals in years
n= estimated porosity, dimensionless

The well yield **Q** is the maximum sustained pumping rate possible for the well as determined from a 24-hour drawdown test; if well yield information is not available, the maximum capacity of the pump installed may be substituted. The daily pumping period $\mathbf{t_d}$ is usually 720 (minutes in 12 hours); if the actual pumping period exceeds 12 hours, then actual period in minutes should be used.

If standard values of $\mathbf{t_d}$ of 720 minutes per day, **P** of 10 years, and a general estimate of n (porosity) are used in Equation 6, the equation reduces (rounded) to:

$$V_{10} = 1{,}800{,}000 \text{ x } Q \qquad (7)$$

Where
V_{10} = the volume of aquifer in cubic feet that supplies ten years of water withdrawals

For simplicity, it is assumed that the volume calculated in Equation 7 is contained in a cylinder centered on the well. To estimate the radius of the cylinder (and therefore the radius of the WHPA around the well) it is necessary to determine or estimate the thickness of the part of the aquifer that supplies water to the well. Thickness may be known or is approximated by the length of the screened portion(s) of the well. Then, the radius can be calculated as:

$$r = \sqrt{\frac{V_{10}}{pb}} \qquad (8)$$

Where:
r = radius in feet
V_{10} = volume of aquifer in cubic feet that supplies 10 years of withdrawals
π = 3.1416
b = the aquifer thickness or length of well screen in feet

Because actual aquifer thickness may be underestimated by well screen length alone, it may be preferable to use the recommended guidelines in Table 1.

Example of Aquifer Source-Volume Estimation

A well drilled into a semi-confined Coastal Plain aquifer is screened for 50 feet and has a yield of 250 gallons per minute. To estimate the ten-year aquifer source volume using equation (7):

V_{10} = 1,800,000 *x* Q = 1,800,000 *x* 250 = **450,000,000 cubic feet**

Assuming an aquifer thickness equivalent to the screen length, the radius of the WHPA calculated using equation (8):

$$r = \sqrt{\frac{V_{10}}{pb}} = \sqrt{\frac{450{,}000{,}000}{3.1416x50}} = \sqrt{2{,}864{,}789} = \mathbf{1{,}693\ feet}$$

Alternatively, using values in Table 1, the radius is estimated to be **2,000 feet**

Table 1. Recommended radii of WHPAs for wells withdrawing from semi-confined and highly confined aquifers.

Well Yield Q[1] (gpm)	Maximum Permitted Withdrawal (Q$_{MPW}$[2]) (gallons)	Aquifer Thickness[3] (ft)	Radius of WHPA (ft) (rounded)
50	36,000	25	1,000
100	72,000	50	1,000
200	144,000	50	1,500
500	360,000	75	2,000
1000	720,000	75	3,000
2000	1,440,000	100	3,500

[1] Maximum sustained well yield or maximum capacity of the pump, in gallons per minute. Read as “up to” the indicated value; e.g., for a well yield of 150 gpm, use line representing 200 gpm.
[2] Maximum Permitted Withdrawal (Q$_{mpw}$) based on 12 hours per day of pump operation.
[3] Aquifer thickness is a value assumed on the basis of the pumping rate.

Other Methods. More sophisticated methods of delineation can provide a more precise delineation of your WHPA, but typically require a high level of expertise, specific data on your aquifer, or both.

- **Analytical methods** involve the use of equations to delineate the boundaries of the WHPA. Specific hydrogeologic input data are required to satisfy the equations; these data can include hydraulic conductivity, transmissivity, hydraulic gradient, and thickness of the saturated zone. Once this information has been obtained, the equations can be used to define features of the WHPA such as the distance to the downgradient divide and the appropriate zone of contribution. The upgradient boundaries can be based on time of travel. This method can be relatively inexpensive, although costs can be high if site-specific hydrogeologic data are not readily available and must be obtained for the delineation.
- **Hydrogeologic mapping** uses geological, geophysical, and dye tracing methods to map flow boundaries and time of travel. To determine the actual flow boundaries, geological studies of the aquifer are undertaken to identify permeability characteristics, areal extent, and aquifer thickness. This method can be used to delineate WHPAs in areas of complex or rapid ground-water flow such as karst aquifers. Application of these delineation techniques requires considerable technical expertise and professional judgement and may become very expensive if field investigations are necessary. It is inappropriate to try to extrapolate data from other areas to your own using this method; it must be site-specific.
- **Numerical models** use computer modeling techniques to simulate the three-dimensional boundaries of an aquifer. The numerical approach uses a grid to simulate the aquifer, with data on water table elevation, hydraulic conductivity, and aquifer thickness input for each point on the grid. Computer models have the advantage of being able to model highly complex aquifers quickly and to simulate the response of the system to proposed management options, such as the operation of a new well. Because a high level of expertise and an extensive data base are required for application, numerical models are potentially the most expensive method of delineation of contributing areas.

Note that the PWS Section will only accept delineations based on these methods if enough good information is available to reliably apply them.

Sophisticated techniques for WHPA delineation may be more precise but also require special expertise and data and have a higher cost.

What about multiple wells? Most PWS systems contain more than one well located relatively close to each other. In many cases, WHPAs delineated for individual wells may overlap. If the overlap is relatively small, you can simply draw your WHPA boundary along the widest boundary created by the overlap. However, to provide for the greatest degree of protection and to promote administrative feasibility, you may need to take a different approach. It is probably not desirable, for example, to leave a “hole” inside your WHPA simply because a small area is not covered by the intersection of several WHPAs centered on individual wells.

One approach is to treat a group of clustered wells as a single well with a pumping rate equal to the total of all the wells. If the wells are arranged in a line, the WHPA may be an ellipse that contains an area equal to the combined WHPAs for all the wells. If wells are grouped in a cluster, you can calculate a WHPA radius for the total of all well yields centered on an imaginary point at the center of the cluster. You may wish to seek expert assistance or consult additional resources in complicated situations (see References and Resources section). It is also a good idea to submit a draft WHPA delineation to the PWS Section for review and approval prior to completing the remaining steps of the WHP Plan.

Which method is right for you? The region the WHPA is in may determine which delineation method is appropriate. Your planning team must evaluate what is technically and economically feasible and technically acceptable. Before making a decision on a delineation method, ask these questions:

- Is the aquifer confined or unconfined?
- Do geologic maps exist for the area?
- Does pump test information exist?
- Is regional ground-water flow direction known?
- Is regional or local hydraulic gradient known?
- Is technical assistance available from the N.C. Rural Water Association or elsewhere?
- Are resources available to retain a consulting hydrogeologist or other professional assistance?

It is usually advisable to consult with staff from the PWS Section or the N.C. Rural Water Association before making a firm commitment on a delineation method. More detailed information on delineation of WHPAs is available in print (Heath, 1991; NCDENR, 1995; Heath and Johnson, 2001; USEPA, 1993).

Pros and Cons of Different Delineation Methods

Method	Advantages	Disadvantages
Calculated Fixed Radius	Easy to do, inexpensive Generally conservative Limited data requirements	Not very accurate May not be appropriate with confined aquifer
Variable Shape	Can be more accurate than calculated fixed radius Low cost if data available Still relatively simple	Requires more information than calculated fixed radius
Ground-water Velocity	Applicable in confined and semi-confined aquifers Estimates realistic WHPA Low cost if data available	Requires site-specific data
Aquifer Source-Volume	Applicable in confined and semi-confined aquifers Estimates realistic WHPA Low cost if data available	Requires some site-specific data Uncertainty in estimation of actual aquifer thickness
Analytical Methods	Widely used Less arbitrary and more accurate than simpler methods	Requires field data Moderate cost Probably requires professional help
Hydrogeological Mapping	Can be used in karst aquifers, other complex situations Can be accurate if good data exist	Data must be site-specific Requires technical expertise May be expensive if field investigations required
Numerical Flow Modeling	Can be highly accurate	Requires extensive field data Requires technical expertise Can be very expensive

Involving the public

Keep your community informed – make sure citizens know what the WHPA is and that its delineation is not an arbitrary or political decision.

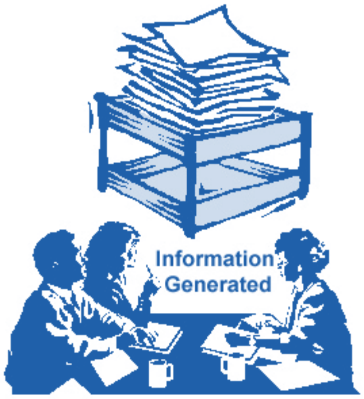
The process of delineating your WHPA is primarily a technical task, best accomplished by the Planning Team with support from appropriate consultants or technical personnel. In this process, it is crucial to gather all pertinent technical information. Thus, it is important to include not only the core group highlighted in Step 1 but also any city and county staff with a technical background in ground water. Your team can also tap the expertise available in local universities, and state agencies. Depending on the delineation method used, it may be necessary to hire a consultant to help complete this task. If so, try to bring in people who could help select an appropriate consultant.

Although general public input may not help the delineation process, it is essential that members of the community understand what the WHPA is and that its delineation is not an arbitrary or political decision. Therefore, it is advisable to inform the public on the process and results of the WHPA delineation effort before proceeding to the next step.

Products that should result from Step 2, to be included in the final plan

When you have completed this step, you should have the following information to include with the final plan you submit to PWS:

1. **Well site evaluation forms for each water supply well** (See Attachment 2).
2. **Maps with WHPA delineations**; either paper copies or in GIS format. The delineation should include full documentation of the method chosen to delineate the area and all data and calculations associated with the result. An example delineation is shown in Attachment 4.



Resources and References

NCDENR. 1995. The North Carolina Wellhead Protection Guidebook. Edited by L.S. Smutko, L.E. Danielson, and G.D. Jennings. North Carolina Department of Environment, Health and Natural Resources Division of Environmental Management Groundwater Section Raleigh, NC.

NCDENR. 1999. North Carolina's Source Water Assessment Program Plan. North Carolina Department of Environment & Natural Resources, Division of Environmental Health, PWS Section.

Heath, R.C. and M.G. Johnson. 2000. Proposed Revisions to the North Carolina Wellhead Protection Program.

USEPA. 1993. Wellhead Protection: A Guide for Small Communities. U.S. EPA EPA/625/R-93-002, Office of Water, Washington, D.C.

There are resources available to help you delineate your WHPA. The North Carolina Rural Water Association has staff dedicated to assisting communities in delineating WHPAs. The NCRWA is on the web at: http://www.ncrwa.com/ and may be contacted at (336) 731-6963.

Another source of help is the PWS Section of the North Carolina Division of Environmental Health. They will review your draft wellhead protection plan (see Step 7) and can assist you in the process of developing a plan. PWS has central and regional offices. This information may be found on the web at: http://www.deh.enr.state.nc.us/pws/. The central office phone numbers is: 919-733-2321 Regional offices are listed by county at: http://www.deh.enr.state.nc.us/pws/counties.htm

Attachments:

Beginning with the next page, you will find attachments that are provided to make it easier for you to prepare your plan document.

Remember, the attachments that are labeled "Example" are only for you to give you ideas.

- **Attachment 1: Glossary of ground-water terms with figures**
- **Attachment 2: Well site evaluation form**
- **Attachment 3: Ground-water recharge rate map for North Carolina**
- **Attachment 4: Example of a partial plan, showing the portions of the plan that result from this step.** The example plan shows you the kind of information that you are expected to include in the plan that you submit for approval. Your final plan will be different than the fictional Town of Clearwater plan that is provided as an example.

Attachment 1: Glossary of Ground-water Terms with Figures

The following terms are often used when discussing ground water and planning for wellhead protection. Many of the terms are illustrated in the accompanying diagrams.

Aquifer – an underground, water-bearing geologic formation that will yield water in a usable quantity to a well or spring.

Capture zone – the area within an aquifer that drains to and is captured by a pumping well. Also known as the zone of contribution (ZOC) or contributing area.

Cone of depression – the depression of the ground-water level around a pumping well caused by the withdrawal of water. Also known as the zone of influence (ZOI) or radius of influence.

Confined aquifer – an aquifer saturated with water and bounded above and below by materials having a lower hydraulic conductivity than the aquifer itself.

Contaminant plume – an elongated and mobile band of a pollutant moving in association with ground water through soil or an aquifer.

Distance – a radius measured outward from the pumping well. Distance is the most basic, and often least accurate, criterion used in delineating a WHPA.

Drawdown – the lowering of the water table surrounding a well during pumping. Drawdown is greatest at the well and decreases with distance from the well.

Ground-water divide – a ridge in the water table from which ground water moves away in right angles in both directions; analogous to a surface watershed divide.

Hydraulic conductivity – the capacity of an aquifer material to transmit water; expressed as the volume of water that will move in a unit time through a unit area at a hydraulic gradient of unity (1.0).

Hydraulic gradient – the slope of the water table along the direction of flow; the change in water level per unit distance, e.g., ft/ft.

Permeability – The ability of a porous medium to transmit water; permeability depends on porosity

Porosity – the volume of openings in soil or rock, expressed as the ratio of the total volume of openings to the total unit volume of soil or rock.

Pumping test – A test performed by pumping a well for a period of time and observing the water level to determine characteristics of the aquifer.

Recharge rate – The volume of water on average that reaches the aquifer from a surface source such as rain. Expressed here in gallons per day per square mile.

Saturated zone – the zone (below the land surface) in which all interconnected openings are filled with water.

Specific yield – the amount of water that will drain from a water-bearing material under the influence of gravity.

Time of travel – the amount of time it takes for water to reach a well from a certain distance.

Transmissivity – the capacity of an aquifer to transmit water; equal to the hydraulic conductivity times the aquifer thickness

Unconfined aquifer – an aquifer that contains both an unsaturated and a saturated zone, i.e., an aquifer not full of water

Water table – the top of the saturated zone in an unconfined aquifer; the level in the saturated zone at which the water is under a pressure equal to atmospheric pressure

Zone of influence (ZOI) – See *cone of depression*.

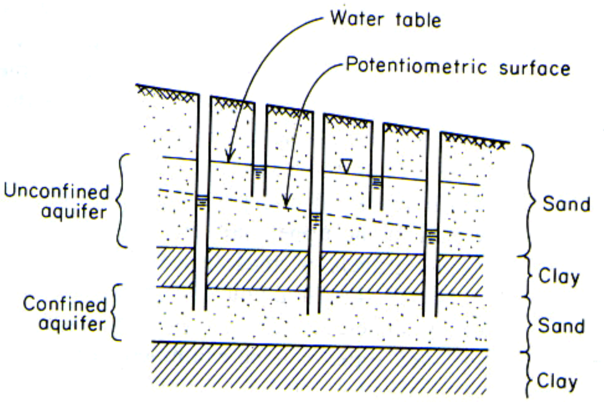


Figure A-1 . Illustration of terms (from Freeze and Cherry, *Groundwater*)

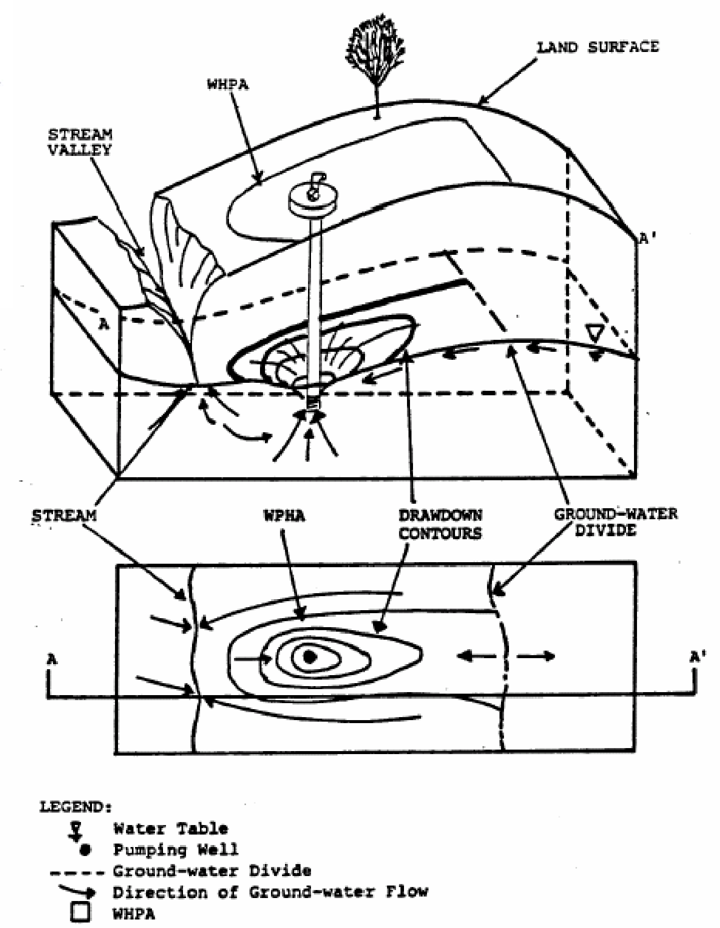


Figure A-3 WHPA delineation using groundwater divides and streams

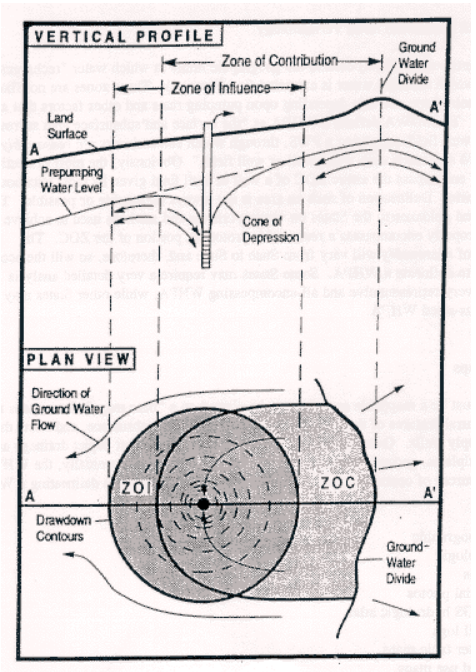


Figure A-2 Illustration of Capture Zone and Zone of Influence

Attachment 2: Well Site Evaluation Form

General Information

*1) Well owner/system name__________________________ 2) Date drilled ____________

*3) Well location (St./Rd. & Town)____

*4) Water supplied to____

5) Source aquifer (if known)____

6) Well depth __________ft.

7) Diameter ____________in.

8) Depth cased ___________ft.

9) Open hole/screen from _________ to ___________ft.

Information from the Well Acceptance Test

10) Date: ______________________ 11) Length: _______________hours

12) Pumping Rate _______________ gpm 13) Depth to Static Water Level:____________ft.

14) Pumping Level ______________ ft. 15) Drawdown _______________ ft.

Well Operation

*16) Pumping rate _______________ gpm *17) Pump Period ____________min/day

Well Location

*18) Latitude: _______________ *19) Longitude: _______________

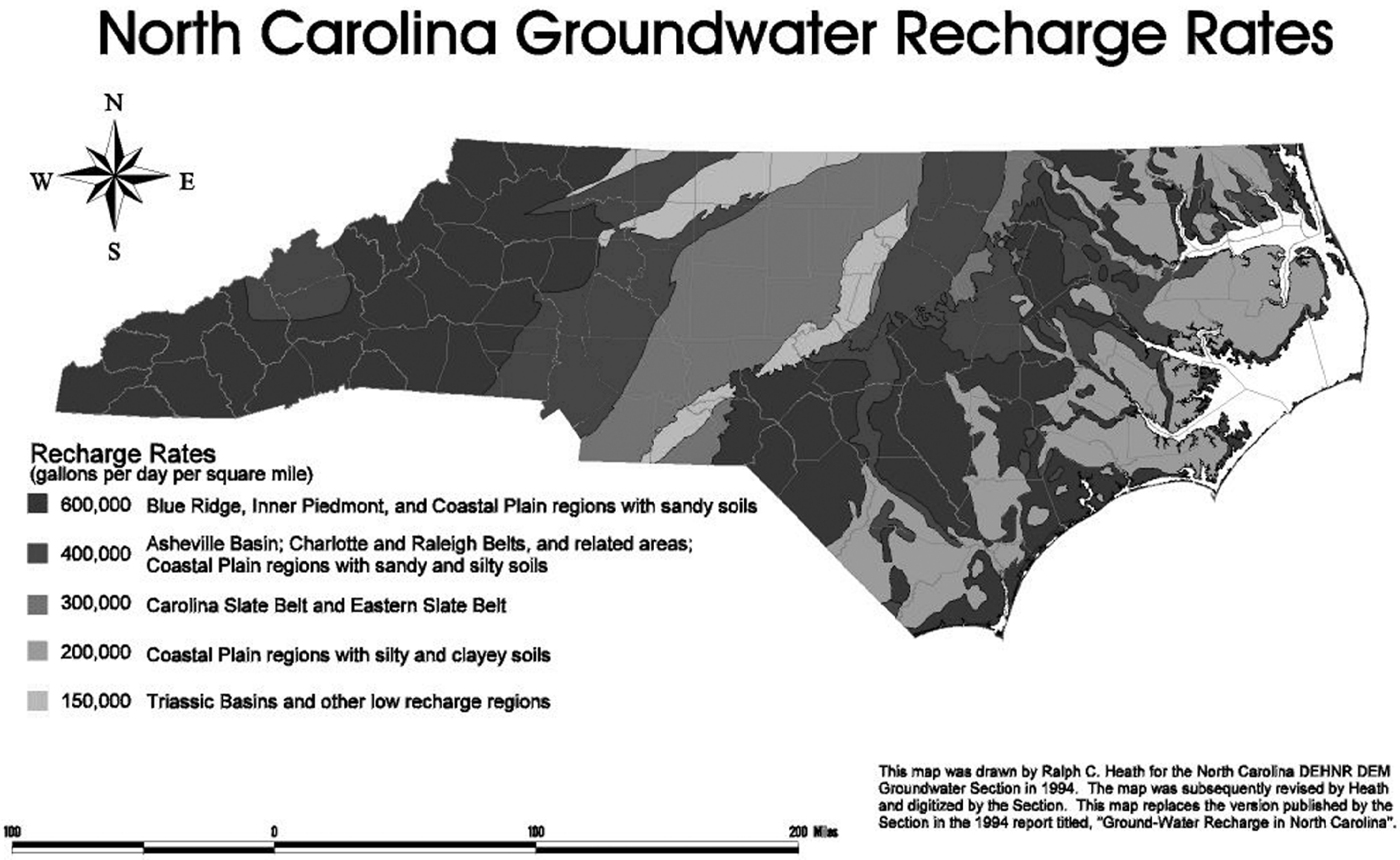
*20) A1:24,000 scale 7.5 minute topographic map showing the well location must also be submitted.

Other information as available:

*Minimum data required for Wellhead Protection Area delineation.
Additional information will improve the accuracy of the delineation.

Prepared by ____________________________ Date __________________ Checked _______________

Attachment 3: Figure showing estimated average recharge rates in North Carolina



North Carolina Groundwater Recharge Rates

This map was drawn by Ralph C. Heath for the North Carolina DEHNR DEM Groundwater Section in 1994. The map was subsequently revised by Heath and digitized by the Section. This map replaces the version published by the Section in the 1994 report titled, "Ground-Water Recharge in North Carolina".

Attachment 4: Example of a partial plan, showing the portions of the plan that result from this step

The Town of Clearwater lies in the central portion of Burns County, approximately 16 miles northwest of Springfield. The Clearwater Water System serves a population of 4,700 people via 2,315 connections and uses three wells to supply its population with water. These wells lie in the Black Creek geological formation consisting of mostly lignitic sand and clay in the Coastal Plain physiographic province of North Carolina. Their water comes from the Black Creek Aquifer that is unconfined in this area and has an estimated average recharge rate of 200,000 gallons per day (gpd) per square mile (mi^2).

Well # 1 is located in a residential area in the southern portion of the town. A well site evaluation form for Well #1 is shown in Figure 1. Well # 2 is located in a rural area south of town and Well # 3 is located in a rural area northeast of town. The topography surrounding the wells is generally flat.

Information about each of the wells was collected by the WHP Planning Team. The well locations are shown on the map in Figure 2. The location of these wells and their maximum production rates, as determined from well acceptance test data, are shown below.

WELL #	LOCATION	DEPTH (FT)	SCREENED FROM (FT)	LATITUDE	LONGITUDE
1	311 Gordon St.	280	147 – 276	35° 11.381’	78° 03.780’
2	1458 SW Church Rd.	295	258 – 290	35° 10.934’	78° 01.140’
3	County Road 1A	294	155 – 289	35° 13.020’	78° 03.780’

The Calculated Fixed Radius method was used to delineate the WHPA. This method is accepted by the NCDENR/PWS Section.

Well #	**Maximum pumping rate**	**Minutes pumped per day**	**Max. permitted daily withdraw (gal/day)**	**Recharge rate (gal/day/mi^2)**	**Well contributing area (mi^2)**	**WHPA (mi^2)**	**WHPA Radius (ft)**
1	800	720	576,000	200,000	2.88	5.76	7,149
2	600	720	432,000	200,000	2.16	4.32	6,192
3	900	720	648,000	200,000	3.24	6.48	7,583

When areas were delineated around each of the wells individually, the areas for wells #1 and #2 overlapped, while the area around well #3 did not overlap either of the other areas. The Planning Team decided that designating a single WHPA using combined pumping rates for all three wells would encompass too large an area and would include land not within the contributing area for any well. Instead, the Planning Team has designated two WHPAs, as shown in Figure 2:

WHPA 1	an oval (dashed line) that includes the calculated fixed radius WHPAs around wells #1 and #2, having an area equal to the combined areas of the WHPAs calculated for wells #1 and #2; and
WHPA 2	a circle around well #3 with a radius of 7,583 feet.

WELL SITE EVALUATION FORM

General Information

*1) Well owner/system name Clearwater Water System 2) Date drilled August 14, 1972

*3) Well location (St./Rd. & Town) 311 Gordon Street, Clearwater

*4) Water supplied to Clearwater

5) Source aquifer (if known) Black Creek Aquifer

6) Well depth 280 ft.

7) Diameter 6 in.

8) Depth cased 280 ft.

9) Open hole/screen from 147 to 276 ft.

Information from the Well Acceptance Test

10) Date: August 21, 1972	11) Length: 24 hours
12) Pumping Rate 800 gpm	13) Depth to Static Water Level: 120 ft.
14) Pumping Level 190 ft.	15) Drawdown 70 ft.

Well Operation

*16) Pumping rate 800 gpm	*17) Pump Period 720 min/day

Well Location

*18) Latitude: 35° 11.381″	*19) Longitude: 78° 03.780″

*20) A1:24,000 scale 7.5 minute topographic map showing the well location must also be submitted.

Other information as available:

Well # 1 is located in a mixed residential area, less than 1 mile north of Well #2

Prepared by Carl Morgan Date January 18, 2002 Checked H.S.

Figure 1. Well Site Evaluation Form for Well #1

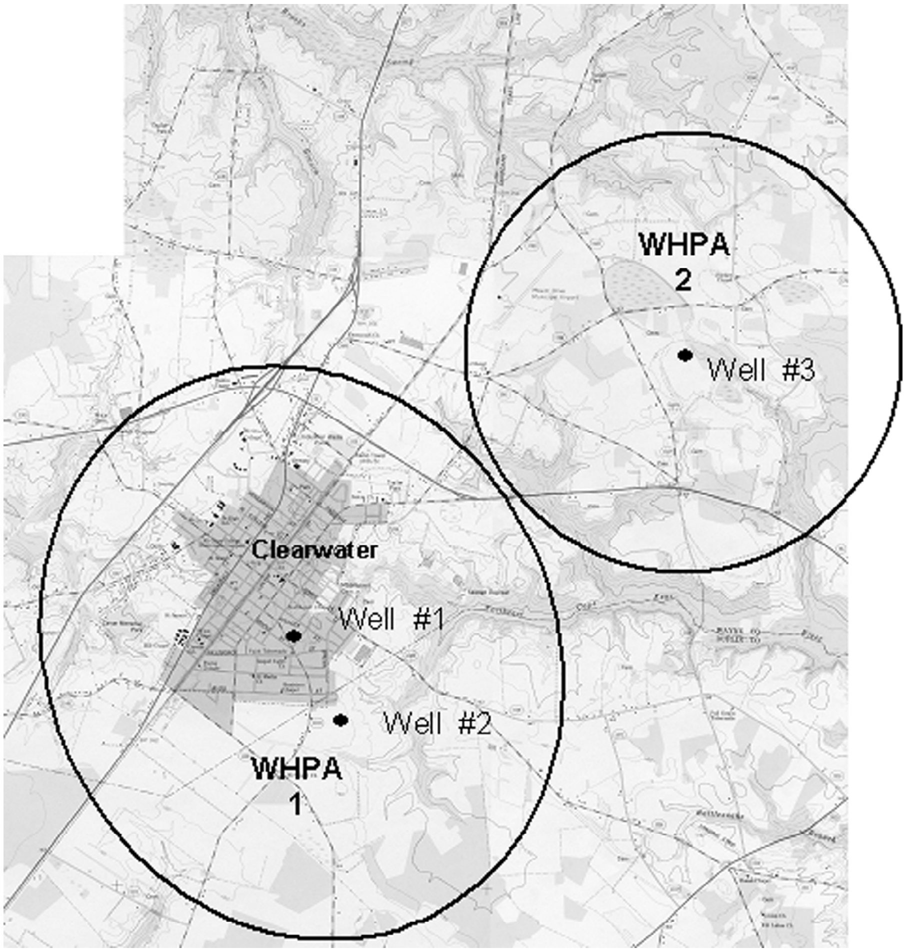


Figure 2. WHPAs for Town of Clearwater