NEW JERSEY GEOLOGICAL SURVEY
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GUIDELINES FOR DELINEATION OF WELL HEAD PROTECTION AREAS IN NEW JERSEY

New Jersey Department of Environmental Protection

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NEW JERSEY DEPARTMENT OF ENVIRONMENTAL PROTECTION

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Cover illustration: An example of a WHPA is shown. The Well Head Protection Area is broken into three tiers; Tier 1, or the 2-year time of travel (TOT), is shown in light gray, Tier 2, or 5-year TOT, is shown in middle gray, and Tier 3, or the 12-year TOT, is shown in dark gray. Ground water movement is from left to right across the picture toward the pumping well near center of Tier 1.

New Jersey Geological Survey

Guidelines for Delineation of Well Head Protection Areas in New Jersey

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"The water that occurs below the surface of the land is invisible and relatively inaccessible and has consequently always possessed an aspect of mystery. What is the mode of its occurrence; what is its quantity; whither does it come; is it stationary or in motion? If in motion, what is its destination and its rate of movement, and what are the forces that propel it through the earth…? These are some of the questions that confront the hydrologists who endeavor to look below the surface. They are questions of almost infinite complexity, involving a great amount of physics and chemistry and almost the whole field of geology."

From Physics of the Earth-IX-Hydrology, page 385, Oscar E. Meinzer, U.S. Geological Survey, 1942.

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Introduction

Background

The 1986 Federal Safe Drinking Water Act Amendments (Section 1428, P.L. 93-523, 42 USC 300 et. seq.) direct all States to develop a Well Head Protection Program (WHPP) Plan for both public community (CWS) and public non-community (NCWS) water-supply wells. New Jersey's WHPP Plan was approved by the U.S. Environmental Protection Agency (EPA) in December 1991. A goal of the WHPP Plan is to prevent contamination of ground-water resources, which provide drinking water to roughly forty-two percent of New Jersey's population. The delineation of Well Head Protection Areas (WHPA's) is one component of the WHPP. The WHPA is the area from which a well draws its water within a specified time frame. Once delineated, these areas become a priority for efforts to prevent and clean up ground-water contamination. Other components of the WHPP Plan include pollution-source inventories, development and implementation of best management practices to protect ground water, land-use planning, and education to promote public awareness of each person's role in protecting our ground-water resources.

The Safe Drinking Water Act Amendments of 1996 (P.L. 104-182) established the need for each State to have a Source Water Assessment Program (SWAP). In New Jersey, source-water assessment areas for all public supply wells will be established by NJDEP using these WHPA delineation methods.

Public supply wells draw water from underground water sources known as aquifers. Aquifers are geologic units that are porous and permeable enough to hold and allow water to flow through them in quantities sufficient to supply wells. The water contained in these aquifers is called ground water. Ground water moves from points of high pressure (often high elevation) to points of lower pressure such as streams, springs, and pumping wells. When a well is pumping, nearby ground water flows toward it. The longer the well pumps, the greater is the distance from which water will flow through the aquifer to the pumping well. For example, pumping a typical community supply well in New Jersey's coastal plain for two years may draw ground water from 1,500 feet away. If the well continues to pump for twelve years, ground water may be drawn from about a mile up-gradient of the well. The time it takes a given particle of ground water to flow to a pumping well is known as the time of travel (TOT). The TOT is directly related to the distance the water has to travel to arrive at the well once it starts pumping. However, for any given TOT, the distance will vary from well to well depending on the rate of pumping and aquifer characteristics such as the transmissivity, porosity, hydraulic gradient, and aquifer thickness. Each WHPA is divided into three sequential tiers based on the TOT component. The tiers are used to assess the relative risk of contamination to the well by placing a higher priority on pollution sources, prevention and remedies in the tiers closest to the wells.

Aquifers are recharged with water from precipitation that percolates through pervious land surfaces and becomes part of the flow of ground water. It is within the WHPA that land uses which introduce pollutants, are most likely to contaminate drinking water sources. Historically, land uses and commercial and industrial facilities and activities have been identified as major sources of ground-water contamination in New Jersey (NJ Water Quality Inventory Report, 1992). These include, but are not limited to: underground storage tanks, septic systems, surface spills, unsecured landfills, leaking drums, above ground storage tanks, road salt piles, and lagoons/surface impoundments.

Once WHPA's are delineated, potential pollution sources may be managed in relation to their location within the WHPA. In addition, protective land uses, such as preserved open space, may be established. In instances where a public supply well has already been contaminated, the WHPA provides investigators with an area in which to search for potential pollution sources and responsible parties.

Under SWAP, the Department has delineated WHPA's for the approximately 2,425 community water supply wells (CWS wells), and will be establishing WHPA's for the roughly 5,000 non-community water water supply wells (NCWS wells) in the near future.

Purpose and Scope

It is the purpose of these guidelines to establish the approved methods for delineation and submission of WHPA's in New Jersey. In accordance with SWAP, the Department will delineate WHPA's for all existing and new CWS and NCWS wells. Based upon their own needs, concerns or requirements for both CWS and NCWS wells, interested parties may perform WHPA delineations at an advanced level as defined later in this guidance.

These guidelines will be used by the Department as well as by outside parties interested in performing delineations. A WHPA delineation may be required as the result of Department regulations, or through a Department-approved remedial investigation or remedial-action work plans. Until such time that regulatory standards for WHPA delineations are established, it is the Department's intent that all public entities require WHPA's to be delineated pursuant to these guidelines.

The focus of this report is to establish the Department's approved methods for conducting delineations, detailing the minimum data requirements, delineation method selection, preferred hydrogeologic parameter and model selection. Use of the prescribed methods will allow interested parties to submit a WHPA delineation for Department review and approval. The report contains requirements for outside parties interested in submitting WHPA delineations to the Department.

Copies of the New Jersey Well Head Protection Program Plan are available from the Division of Watershed Management, P.O. Box 418, Trenton, NJ 08625, or by calling (609) 777-1053, or on the internet at: www.state.nj.us/dep/watersupply/swap.htm.

Delineation Impacts

People in New Jersey who obtain water from public supply wells will benefit by WHPA delineations. The source of their water will ultimately be better protected and preserved through the implementation of the WHPP and the SWAP. The WHPA delineations help the Department achieve several of its strategic goals including clean and plentiful drinking water for all of New Jersey's residents and the resulting reduction in risk to human health that comes with safe drinking water.

Those owning or operating properties containing potential or existing pollutant sources within a designated WHPA will also be affected. The WHPA will provide a clear understanding and justification for the special need of pollutant source control. The source controls instituted in these areas will range from public education to appropriate regulation, depending on the nature of the potential pollutant source, the risk of discharge, and the proximity to the well.

It is hoped that the preventive and voluntary nature of the WHPP and SWAP will encourage cooperative efforts at the county and municipal government levels to protect an essential and shared public resource, the underground water supply. The delineation of WHPA's will help communities understand the nature of their ground-water resources and provide protection for their drinking water supply. Geographic targeting through WHPA delineations enables decision-makers to designate drinking water sources within WHPA's a priority for ground-water protection efforts.

Ground water is vulnerable to contamination and once polluted, it is difficult and costly to clean up. Contaminated ground-water supplies are often abandoned and replaced by more costly surface-water supplies. The value of good-quality ground water can best be understood by comparing its cost with that of treated ground water or an alternative surface-water supply. In many areas, ground water is relatively inexpensive when compared to surface water. The EPA estimated that, in 1991, it cost about one hundred dollars to obtain a million gallons of untreated ground water. In areas of New Jersey where ground-water supplies were replaced with surface water, the cost increased to a thousand dollars or more. The EPA estimated that a switch from untreated ground water to a surface water supply in 1991 would result in a $340 increase per household per year (USEPA, 1991, page 13.). Given New Jersey's reliance on ground water as an integral source of drinking water, the potential annual cost resulting from ground-water contamination is hundreds of millions of dollars.

The costs of remediation or of developing replacement water sources is burdensome and in some cases may be prohibitive for local governments or utilities. Preventing ground-water pollution is clearly the most cost-effective approach to maintaining ground-water resources. The Department's Source Water Assessment Plan (SWAP) emphasizes prevention as the first line of defense to protect New Jersey's ground-water resources. Well head protection is a unique solution that promotes the enlightened self-interest of communities who depend on ground water for their drinking water. The intent is to reduce the potential for contamination by both public and private parties, thereby requiring less treatment and remediation costs.

Public Comment

An earlier draft of this report was published as "Draft Guidance for Well Head Protection Area Delineations in New Jersey" (Spayd, 1998). The draft technical guidance was distributed to interested parties and posted on the Department's SWAP web page. Public comments were solicited at that time and considered in the development of this report.

Acknowledgements

The New Jersey Geological Survey (NJGS) compiled these guidelines with the assistance of the WHP and SWAP Technical Advisory Committees. Special thanks are due to Tom McKee, Bob Kecskes, Terri Romagna and Kim Cenno of the Division of Watershed Management; Judy Louis of the Division of Science, Research and Technology; Barker Hamill, Sandy Krietzman, and Pat Bono of the Bureau of Safe Drinking Water; Robert Nicholson and Eric Vowinkel of the U.S. Geological Survey (USGS); and Karl Muessig, Bob Canace, Jeff Hoffman, Jim Boyle, Laura Nicholson, Bill Mennel, Eric Roman, Ted Pallis, Joe Rich, Walt Marzulli, and Doug Rivedal of NJGS. Former Department employees Dan Van Abs and Emery Coppola also provided significant contributions. Participants in the SWAP Technical Advisory Committee included staff from the Department, EPA, USGS, water purveyors, environmental and watershed associations, as well as local and county health and planning organizations. Participants in the WHP Technical Advisory Committee included staff from:

New Jersey Department of Environmental Protection
Office of Environmental Planning
New Jersey Geological Survey
Bureau of Water Allocation
Bureau of Safe Drinking Water
Division of Science, Research and Technology
Division of Solid Waste Management
Bureau of Operational Ground Water Discharge Permits
Bureau of Underground Storage Tanks
Bureau of Environmental Evaluation and Risk Assessment
New Jersey Department of Agriculture
New Jersey Department of Transportation
New Jersey Pinelands Commission
Delaware River Basin Commission
U.S. Environmental Protection Agency
U.S. Natural Resources Conservation Service
U.S. Geological Survey

General Delineation Requirements

Delineation Tiers

A WHPA will consist of three tiers, each based on a time of travel to the well. The outer boundaries of these tiers will have the following times of travel:

Tier 1 = two years (730 days).
Tier 2 = five years (1,826 days).
Tier 3 = twelve years (4,383 days).

The portion of the zone of contribution designated as the WHPA is based upon the TOT of the ground water to a pumping well. The TOT's are based on the need to assess the relative risk of contamination to the well, allowing priority to sources that pose an imminent threat.

The TOT for the outer boundary of Tier 1 is two years. This TOT is based on findings that bacteria have polluted wells as far as a 170 day TOT from wells, and that viruses have survived in ground water for up to 270 days (Canter, Knox, and Fairchild, 1987; USEPA, 1987). Generally, pollution does not move in a uniform front, so that a TOT represents an average. Significant pollution may reach a well before the average TOT. In addition, once a pollution plume gets too close to a water-supply well, plume containment usually is not feasible without an impact on the yield of the well. The two-year TOT provides a reasonable margin of safety beyond the 170 and 270-day figures.

The boundary for Tier 2 is five years. The Department is not reasonably certain that it can ensure containment of pollution from a known discharge or restoration of the aquifer at TOT's ranging from two to five years. The Department has significantly revised its procedures for pollution case management so that enforcement or public funding of remedies is expedited for cases which threaten or pollute water-supply wells. However, even with implementation of these procedural changes in WHPA's, a lag time between case identification and the initiation of effective remedies still exists. Selection of the five-year TOT was based on the "smearing" effect observed in pollution plumes (caused by adsorption/desorption and the variable rate of pollutant travel through pores), the acceleration of ground water once it comes close to a pumping well, complexity of ground water pollution cases and lag-time estimates for remediation given that approximately 40 percent of all pollution cases must be managed by the Department due to the lack of a cooperating responsible party.

Beyond Tier 2, the Department is reasonably sure that a viable pollution mitigation response is possible for significant, known discharges of pollutants. The purpose of Tier 3, then, is to ensure sufficient monitoring of potential pollution sources so that responses may be made. Theoretically, Tier 3 could extend to the boundaries of the complete zone of contribution. However, the WHP Technical Advisory Committee determined that such an extensive area is not needed in New Jersey. Minor pollutant sources sufficiently distant from it may not pose a significant risk to the well, due to attenuation and dilution. A preliminary analysis of pollution cases in seven counties indicated that a TOT of 10 to 15 years encompasses the full length of most pollution plumes identified (almost all are less than one mile, but many exceed 2,000 feet) (NJDEPE, 1991, page 21.). In addition, a rough analysis of dilution ratios suggests that a 10 to 15 year TOT would provide sufficient dilution and attenuation to minimize the risk of well pollution. It is clear that most sources outside of a TOT of 15 years are either too minor to be of special concern or are major enough to ensure that current Department regulations will protect the water supply. Most significant sources of future discharges, within the zone of contribution but far from the well, will be sufficiently regulated by the Department for Tier 3 and outside of Tier 3. Therefore, a TOT of 12 years was deemed sufficient.

Delineation Methods

A method of WHPA delineation should be selected from and be in accordance with the methods defined in the Approved Delineation Methods section of this report.

WHPA delineation methods, with the exception of the two Calculated Fixed Radius (CFR) methods, should be performed by a qualified ground-water professional.

If a well pumps from more than one aquifer, the WHPA delineation method applicable to the uppermost aquifer will be used with the full pumping rate assigned to the uppermost aquifer.

If a well draws water from a confined aquifer, and the vertical time of travel for ground water moving from the surface downward through the confining unit at the well or for the horizontal time of travel from the edge of the confining unit to the well exceeds 12 years, as determined by the Department, then all three tiers of the WHPA will be established as the 50-foot, owner-controlled zone mandated by Public Water System Construction Regulations (N.J.A.C. 7:10-11.1). For these wells, the land-surface area, where discharges affecting ground water may occur, is beyond Tier 3. The USGS has conducted a study for the Department, which included development of a method to evaluate a well's sensitivity to contamination (Storck, 1997). USGS determined that all wells in glacial and bedrock aquifers in New Jersey should be considered to be drawing water from the land surface within twelve years, unless site-specific data prove otherwise. For wells drawing water from coastal-plain aquifers, USGS determined that the specific location of the well screen and its relation to overlying confining units must be evaluated to determine if water recharging the aquifer reaches the well within 12 years.

A pre-application conference is strongly recommended for all applicants interested in using an advanced delineation method that is not defined in these guidelines. Confirmation or denial of the use of an alternative delineation method will be given by the Department in writing.

Approved Delineation Methods

The selection of appropriate delineation methods involved balancing several factors, for example: WHPP goals, the diverse hydrogeology in the State and the availability of data. Through the work of the WHP Technical Advisory Committee (comprised of technical experts from state and federal government), methods were identified and assessed that would define the zone of contribution of the well. Following A-5015, approved by the Legislature in its 1991 session, the Department will delineate WHPA's for all CWS wells. The WHP Technical Advisory Committee recognized at the beginning of the delineation discussion that it would not be possible, due to cost and staff constraints, to collect site-specific well and aquifer parameter data for each of the approximately 2,425 CWS wells in the State. It was determined that existing data including regional attributes would be used for Department WHPA delineations. The Department will perform its delineations under SWAP/WHPP within the Safe Drinking Water Permitting Program using, at a minimum, the combined model/CFR method on all existing CWS wells and on all new CWS wells. Where adequate hydrogeologic studies and models exist, and Department resources allow, the Department may perform advanced delineation(s).

The delineation method used for a well is dependent on the type of well, hydrogeologic setting for that well, and the availability and reliability of data. The hydrogeologic situation depends on the geology of the aquifer, and the presence of well interference effects, hydrologic boundaries, aquifer heterogeneities, and aquifer anisotropy. This section of the report identifies the acceptable methods with a differentiation made between CWS and NCWS wells.

The Federal mandates for the WHPP and SWAP require that States include NCWS wells in their program plan. In general, fewer well and aquifer parameters are available for NCWS wells due to the nature of the population they serve and a historical lack of reporting requirements. For these reasons, and time, and economic constraints, the Department will delineate WHPA's for all NCWS wells using the CFR Calculation Method. In recognition of the need to minimize the pollution risk to these wells, while considering the limited hydrogeologic expertise that may be available to the well owners to perform their own WHPA delineations, a matrix was developed from which a generic CFR could be determined (Table 1). This matrix was developed using ranges of pumping rates and aquifer thickness as well as an estimated effective porosity. The values in the matrix represent standard values rounded to the nearest ten feet.

Delineation Method Selection

The CFR matrix method is an acceptable method only for NCWS wells whose pumping rate does not exceed 70 gallons per minute.

The CFR calculation method is an acceptable method for NCWS wells at this time. This method will also be used for the CFR portion of any WHPA using the combined model/CFR method. In the future as resources permit, NCWS wells pumping 70 GPM or greater may be delineated by combined model/CFR method.

The combined model/CFR method is an acceptable method for all public water-supply wells. This is the minimum acceptable method for public community water wells (CWS).

The non-CFR model method, the three-dimensional model method, and advanced delineation model are acceptable methods for all public water-supply wells located in areas that have a detailed local and regional water table mapping available, and sufficient accurate data on aquifer recharge, well interference, hydrologic boundaries, aquifer heterogeneities, and aquifer anisotropy.

CFR Matrix Method

The CFR matrix method uses predetermined values given in table 1. The procedure to delineate a WHPA using this method will be as follows:

1. Select table 1a or 1b depending on the type of aquifer from which the well pumps:

a. Table 1a will be used for unconsolidated glacial and coastal-plain aquifers consisting of sand and gravel.

b. Table 1b will be used for all bedrock aquifers including those consisting of sandstone, conglomerate, shale, limestone, dolomite, granite, gneiss, diabase, and other sedimentary, igneous or metamorphic rocks.

2. Find the Tier 1 portion of the selected table, and in the left column of the table find the row with the range that includes the well's pumping rate.

3. In the top row of the table, find the column with the range that includes the well's aquifer thickness.

4. Select the Tier 1 CFR from where the pumping rate row and aquifer thickness column intersects.

5. Repeat paragraphs 2 through 4 above, for Tier 2 and Tier 3.

6. The CFR value for each tier will be used to define the radius of a circle, which will be centered on the well to complete the WHPA delineation. A map of the WHPA delineation, including all three tiers, will be drawn according to the delineation mapping requirements section.

CFR Calculation Method

The CFR calculation method will be used to generate the CFR values by using the following formula:

$$CFR = \sqrt{\frac{61.3Qt}{n_e b}}$$

where:

CFR = Calculated fixed radius in feet
Q = Pumping rate in gallons per minute
t = Time of travel in days (that is, 730, 1,826, or 4,383 days)
61.3 = Conversion factor [(1440 min/day)/(7.48 gal/cu ft)]/3.14
n_e = Effective porosity
b = Aquifer thickness in feet

This method requires the pumping rate, time of travel, effective porosity, and aquifer thickness, which must be selected in accordance with the Data Selection and Parameter Estimation section of this report. The calculation will be made for the appropriate time of travel for each tier. The CFR value for each tier will be used to define the radius of a circle, which will be centered on the well to complete the WHPA delineation. This method is conservative because it does not include recharge in the calculation. However, this was determined to be appropriate as the larger size of the CFR offsets inaccuracies due to the lack of site-specific data and use of the lowest level of delineation. A map of the WHPA delineation, including all three tiers, will be drawn according to the delineation mapping requirements section.

Table 1a. Calculated fixed radius in feet. Unconsolidated Glacial and Coastal Plain aquifers consisting of sand and gravel; effective porosity = 25%.

Tier 1, two year time of travel Aquifer Thickness (feet)						
Pumping Rate (gpm)	1-50	51-100	101-200	201-300	301-400	401-500
<1-10	190	110	80	60	50	40
11-20	330	190	130	100	90	80
21-30	420	240	170	130	110	100
31-40	500	290	200	160	130	120
41-50	570	330	230	180	150	130
51-60	630	360	260	200	170	150
61-70	680	390	280	220	180	160
Tier 2, five year time of travel Aquifer Thickness (feet)						
Pumping Rate (gpm)	1-50	51-100	101-200	201-300	301-400	401-500
<1-10	300	170	120	90	80	70
11-20	520	300	210	160	140	120
21-30	670	390	270	210	180	160
31-40	790	460	320	250	210	190
41-50	900	520	370	280	240	210
51-60	990	570	410	310	270	230
61-70	1080	620	440	340	290	250
Tier 3, twelve year time of travel Aquifer Thickness (feet)						
Pumping Rate (gpm)	1-50	51-100	101-200	201-300	301-400	401-500
<1-10	460	270	190	150	120	110
11-20	800	460	330	250	210	190
21-30	1040	600	420	330	280	240
31-40	1230	710	500	390	330	290
41-50	1390	800	570	440	370	330
51-60	1540	890	630	490	410	360
61-70	1670	960	680	530	450	390

Table 1b. Calculated fixed radius matrix in feet for bedrock aquifers consisting of sandstone, conglomerate, shale, limestone, dolomite, granite, gniess, diabase, and other sedimentary, igneous and metamorphic rocks; effective porosity = 2%.

Tier 1, two year time of travel Aquifer Thickness (feet)						
Pumping Rate (gpm)	1-50	51-100	101-200	201-300	301-400	401-500
<1-10	670	390	270	210	180	160
11-20	1160	670	470	370	310	270
21-30	1500	860	610	470	400	350
31-40	1770	1020	720	560	470	420
41-50	2010	1160	820	630	540	470
51-60	2220	1280	910	700	590	520
61-70	2410	1390	980	760	640	570
Tier 2, five year time of travel Aquifer Thickness (feet)						
Pumping Rate (gpm)	1-50	51-100	101-200	201-300	301-400	401-500
<1-10	1060	610	430	330	280	250
11-20	1830	1060	750	580	490	430
21-30	2370	1370	970	750	630	560
31-40	2800	1620	1140	890	750	660
41-50	3170	1830	1300	1000	850	750
51-60	3510	2030	1430	1110	940	830
61-70	3810	2200	1560	1210	1020	900
Tier 3, twelve year time of travel Aquifer Thickness (feet)						
Pumping Rate (gpm)	1-50	51-100	101-200	201-300	301-400	401-500
<1-10	1640	950	670	520	440	390
11-20	2840	1640	1160	900	760	670
21-30	3670	2120	1500	1160	980	860
31-40	4340	2500	1770	1370	1160	1020
41-50	4920	2840	2010	1560	1310	1160
51-60	5440	3140	2220	1720	1450	1280
61-70	5910	3410	2410	1870	1580	1390

Combined Model/CFR Method

The combined model/CFR method was chosen as the minimum method for CWS wells, and will be used by the Department for WHPA delineations for CWS wells. This method was chosen based upon the Department's need to provide a low cost, relatively accurate estimate of the WHPA using available data on the characteristics of the well (pumping rate and depth) and the regional characteristics of the aquifer (hydraulic gradient direction and magnitude, transmissivity, anisotropy, effective porosity, thickness, and hydrologic boundaries) using the best available data.

The combined model/CFR method combines the CFR calculation method defined above with a two-dimensional ground-water flow model that properly accounts for hydraulic gradient, aquifer transmissivity, effective porosity, aquifer saturated thickness, aquifer anisotropy, pumping rate of the well, and time of travel.

The following steps will be taken:

1. The CFR for Tier 1 and Tier 2 will be calculated as described in the CFR calculation method. No CFR for Tier 3 is used in this method.

2. Determine the regional hydraulic gradient (see page 13).

    a. The hydraulic gradient magnitude and direction will be calculated from a regional water-table map, when available, over a distance from the well to one-mile upgradient of the well.

    b. When no satisfactory regional water table map is available, the hydraulic gradient magnitude may be estimated by multiplying the topographic gradient, calculated over a distance from the well to one-mile upgradient of the well, by 0.5. In some aquifers, especially bedrock aquifers, a reasonable estimate of the regional hydraulic gradient may not be possible. In these cases, the gradient may be set to zero.

3. Determine aquifer anisotropy. For some aquifers, a reasonable estimate of anisotropy may not be possible. In these cases the anisotropy ratio should be set to 1:1. (table 2.)

4. The ground-water flow model will be used to calculate the zone of contribution of the well for the times of travel established for Tier 1, Tier 2, and Tier 3.

5. The long axis of the calculated zone of contribution will be aligned with the regional ground-water flow direction as shown in figure 1.

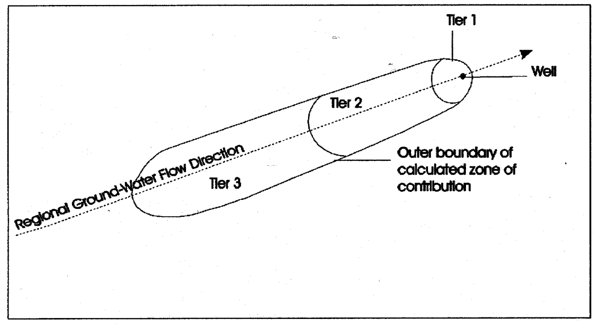

Figure 1 : Long axis of zone of contribution is aligned in the direction of the regional ground-water flow direction

6. A 20-degree angle of rotation, or an angle of rotation determined from site-specific data, will be applied to the model results. The results will be rotated, using the well as the pivot point, by the angle of rotation both clockwise and counter-clockwise, for each tier as shown in figure 2. For a discussion of "angle of rotation", see hydraulic gradient in the Data Selection and Parameter Estimation section of this report.

7. The CFR portion of the WHPA will be superimposed on the results of the ground-water model portion of the WHPA as shown in figure 3. The CFR component was added to account for potential inaccuracies in estimating well characteristics and properties of the aquifer, as well as to account for potential pumping interference effects which are common at public water systems in New Jersey.

8. The resulting outer boundary of the combined CFR and ground-water model portions will then be established for each tier as shown in figure 4.

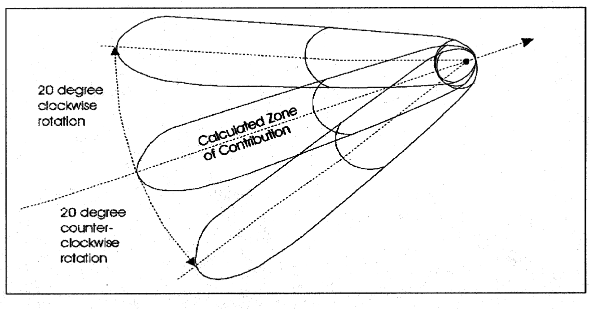

Figure 2. Clockwise and counter-clockwise 20-degree angle of rotation applied to calculated zone of contribution using the well as the pivot point.

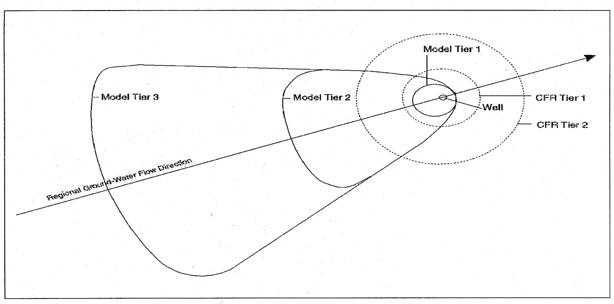

Figure 3. CFR portion of WHPA superimposed on the results of the ground-water model portion of the WHPA.

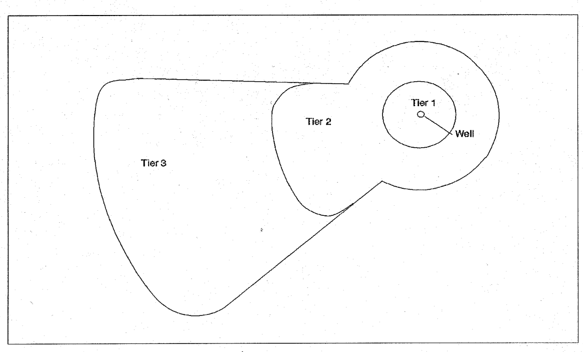

Figure 4. Resulting outer boundary of the combined CFR and model portions established for each tier of the WHPA delineation.

9. The outer boundary of the WHPA delineation may be truncated by appropriate hydrologic boundaries such as major rivers and aquifer boundaries. The resulting boundary will be the WHPA delineation for the well, which will be drawn according to the delineation mapping requirements section.

An example of the type of model the Department and others may use as part of this method is the RESSQC portion of the EPA WHPA Model, defined in the publication, "WHPA: A Modular Semi-Analytical Model for the Delineation of Well Head Protection Areas, March 1991." The model is available through the International Ground Water Modeling Center, Colorado School of Mines, Golden, Colorado, 80401-1887. The appropriate well pumping rate and aquifer values for saturated thickness, hydraulic conductivity, hydraulic gradient and magnitude, and effective porosity are critical to perform the model. Site-specific data, especially for hydraulic gradient, increase the level of model accuracy. Selection of these values is discussed in the Data Selection and Parameter Estimation section.

The NJGS has developed a computer program called "OUTPATH" that will apply the angle of rotation and aquifer anisotropy to outputs from the RESSQC version of the EPA WHPA model and create a file of the WHPA that can be incorporated into a geographic information system (GIS). It is available upon request from NJGS.

Non-CFR Model Method

When a regional water table map is available and aquifer recharge and well interference are accounted for in the model, no CFR is needed for the WHPA delineation. The non-CFR model method will use a two-dimensional ground-water flow model that properly accounts for hydraulic-head distribution, aquifer recharge, well interference, aquifer transmissivity, effective porosity, aquifer saturated thickness, pumping rate of the well, time of travel, aquifer anisotropy, hydrologic boundaries, and aquifer heterogeneities.

The following steps will be taken:

1. For advanced delineations requiring a model grid, the grid cells should be sized to allow accurate locations of pumping wells and the resulting ground-water flow paths. Grid cells containing pumping wells should be no greater than 100 feet in length or width. The maximum allowable length or width of a grid cell in any such model will be 500 feet. The maximum allowable thickness of any layer in the model will be 100 feet. The model should be subject to a sensitivity analysis, and be calibrated, in a manner acceptable to the Department, so that simulated results are acceptably close to field conditions.

2. The ground-water flow model will be used to calculate the zone of contribution of the well for the times of travel established for Tier 1, Tier 2, and Tier 3 as shown in figure 5.

3. A 20-degree angle of rotation, or an angle of rotation determined from site-specific data, will be applied to the model results. The results will be rotated, using the well as the pivot point, by the angle of ro-

tation of rotation both clockwise and counter-clockwise, for each tier as shown in figure 6.

4. The outer boundary of the WHPA delineation may be truncated by appropriate hydrologic boundaries if warranted. The resulting outer boundary of the rotated tiers will then be established as shown in figure 7. This will be the WHPA delineation for the well, which will be drawn according to the delineation mapping requirements section.

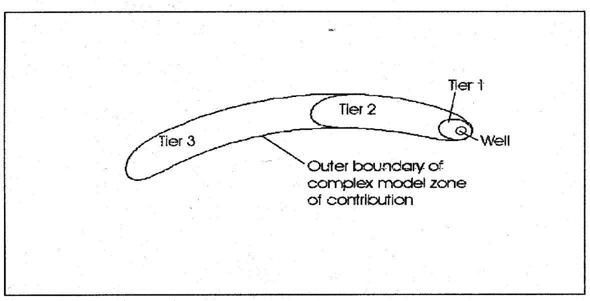

Figure 5. Non-CFR model method zone of contribution example**.**

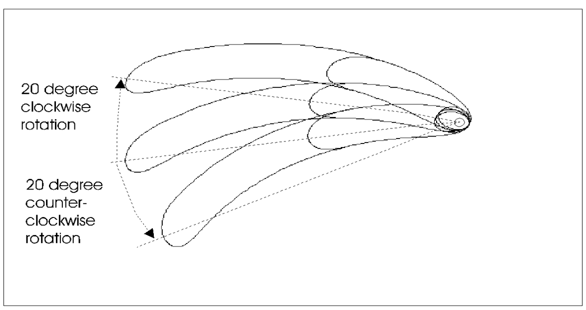

Figure 6. Clockwise and counter-clockwise 20-degree angle of rotation applied to non-CFR model method of contribution using the well as the pivot point.

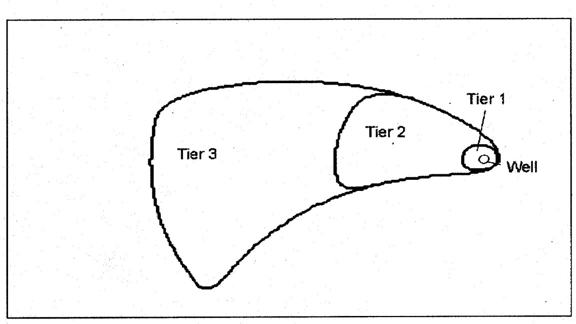

Figure 7. Outer boundaries of the rotated tiers are established as the WHPA delineation.

Three-Dimensional Model Method

The three-dimensional model method will use a three-dimensional, numerical ground-water flow model that properly accounts for hydraulic-head distribution, aquifer transmissivity, effective porosity, aquifer saturated thickness, pumping rate of the well, time of travel, partial penetration of the aquifer by the pumping well, well interference, hydrologic boundaries, aquifer recharge, aquifer heterogeneities, aquifer anisotropy, and any other relevant site-specific conditions, as appropriate for the area surrounding the well.

The following steps will be taken:

1. For advanced delineations requiring a model grid, the grid cells should be sized to allow accurate locations of pumping wells and the resulting ground-water flow paths. Grid cells containing pumping wells should be no greater than 100 feet in length or width. The maximum allowable length or width of a grid cell in any such model will be 500 feet. The maximum allowable thickness of any layer in the model will be 100 feet. A sensitivity analysis and calibration should be performed on the model, in a manner acceptable to the Department, so that simulated results are acceptably close to field conditions.

2. The ground-water flow model will be used to calculate the zone of contribution of the well for the times of travel established for Tier 1, Tier 2, and Tier 3 as shown in figure 5.

3. A 20-degree angle of rotation, or an angle of rotation determined from site-specific data, will be applied to the model results. The results will be rotated, using the well as the pivot point, by the angle of rotation both clockwise and counter-clockwise, for each tier as shown in figure 6. When using the three-dimensional model method, the rotated area should be truncated by appropriate hydrologic boundaries.

4. The resulting outer boundary of the rotated tiers will then be established as shown in figure 7. This will be the WHPA delineation for the well, which will be drawn according to the delineation mapping requirements section.

5. As an alternative to incorporating an angle of rotation when using the three-dimensional model method, a systematic evaluation of the model sensitivity to different combinations of model parameters, over appropriate ranges, may be conducted. This should include seasonal and spatial variation of appropriate model-input parameters. This will require delineating a WHPA for each acceptable combination. The outer limits of the resulting individual tier delineations will

constitute the WHPA, which will be drawn according to the Delineation Mapping Requirements section.

Advanced Delineations and WHPA Revisions

The delineation methods in this report reflect a hierarchy of increasing degree of modeling sophistication and increasing data requirements for the model used to delineate the WHPA. The principle behind this delineation hierarchy is to achieve an increasing degree of accuracy for the WHPA to the degree that methods and available data allow improved simulation of real hydrologic conditions.

The concept of performing advanced delineations is based on two principles. First, where data are available, an advanced delineation will likely provide a WHPA that is more accurate. Secondly, it is conceivable that an interested party, such as a water purveyor or a regulated potential or existing pollutant source, may wish to perform an advanced delineation to provide certainty regarding the application of a WHPA to a specific geographic location. Situations such as a well that receives a portion of its water from a nearby river that has good hydraulic connection to the aquifer, or a well field that is affected by well interference are also good candidates for an advanced delineation.

Because the Department will be performing WHPA delineations on all public water system wells, only delineations submitted by outside parties, which are completed at a level higher than that undertaken by the Department will be reviewed.

Interested parties who feel that a more advanced delineation for a NCWS well is required, and volunteer to perform a WHPA delineation, will use the same methods used for CWS well delineations.

The three-dimensional model method, which uses a numerical model, is the highest level of WHPA methods described in this report because it has the potential to incorporate and evaluate all components of the ground-water system around the pumping well. The Department does not necessarily consider numerical modeling superior to all other techniques for all applications. Numerical modeling is costly and data intensive. It may not automatically result in delineations that are measurably superior to less rigorous and less time-intensive analytical and semi-analytical methods, but, when done properly with good site-specific data, it may provide significant insights into the location of the WHPA.

For public water-supply wells with an existing WHPA delineation completed by the Department, the method selected for a revised delineation should meet the following requirements:

1. The method should be selected from the methods defined in this report and meet the selection requirements listed in the Delineation Method Selection section; and

2. The method should be a more advanced method than that used for the delineation of the existing WHPA, or must be an equivalent method used with more reliable site-specific data, as determined by the Department.

3. For advanced delineations requiring a model grid, the grid cells must be sized to allow accurate locations of pumping wells and the resulting ground-water flow paths. Grid cells containing pumping wells must be no greater than 100 feet in length or width. The maximum allowable length or width of a cell in any such model will be 500 feet. The maximum allowable thickness of any layer in the model will be 100 feet.

The Department intends to rely upon the American Society for Testing and Materials (ASTM) ground-water modeling standards listed in the resource section of this report. Ground-water professionals submitting WHPA's should follow these standards.

Data Selection and Parameter Estimation

The selection of values for hydraulic gradient, aquifer transmissivity, effective porosity, aquifer saturated thickness, pumping rate, well radius and anisotropy for all delineations must be in accordance with the order specified in table 2. For all WHPA methods, each variable listed in table 2 should be selected, when feasible, based on the first selection procedure given in table 2. If the data for the first selection are not available, the second selection should be used. If the data for the second selection are not available, the third selection should be used. Where values can not be determined from table 2 it may be obtained from the NJGS, from a published source, or other source acceptable to the Department.

Hydraulic Gradient

Hydraulic gradient has two components: magnitude and direction. The magnitude is measured as the slope of the water table, representing the change in elevation of the water table over a unit distance. The direction of the hydraulic gradient, often referred to as the "angle of ambient flow," is the azimuth of the maximum slope of the water table at a specific point.

The hydraulic gradient varies over space and time, and is affected by a variety of local and regional factors. For WHPA delineation purposes, the regional hydraulic gradient is the most useful.

For some delineation methods, the hydraulic gradient magnitude and direction will be calculated from a regional water-table map in the area upgradient of the well over a distance of one mile. The distance of one mile was selected as representative of a "regional" gradient, and is reasonable when compared to the calculated lengths of typical WHPA's representing hydrogeologic and operational conditions found in New Jersey.

In instances where it is difficult to calculate the hydraulic gradient within a one-mile span due to rapid changes in the water-table gradient or direction, or due to the location of hydrologic boundaries, the gradient magnitude and direction will be calculated over an appropriate distance of less than one mile.

In areas of the State where regional water-table maps do not exist, the magnitude and direction of the regional hydraulic gradient may be approximated based on topography, in the area upgradient of the well. This is determined by using the change in land surface elevation over a distance of one mile in the aquifer from which the well is pumping. This approach recognizes that the water table is usually a subdued replica of topography.

To quantify the relationship between topography and the water table, the NJGS observed topographic and hydraulic gradients in three drainage basins in the New Jersey Coastal Plain - the Great Egg Harbor, Mullica, and Toms River Basins.

Topographic and hydraulic gradients for selected intervals were compared for 128 line segments each approximately one mile in length.

A statistical analysis of these data suggested that a reasonable estimate of the hydraulic gradient in the Coastal Plain could be obtained by multiplying the topographic gradient by 0.5. Thus, a conversion factor of 0.5 will be used to convert a known topographic gradient, over a distance of one mile in the area upgradient of the well, to the hydraulic gradient magnitude, when lacking a regional water-table map. Research will continue to better define this relationship in other hydrogeologic regions of the State.

The hydraulic gradient direction or angle of ambient flow, is a very important parameter for a WHPA delineation. In certain hydrogeologic settings, especially those with a relatively steep hydraulic gradient, small errors in selection of the angle of ambient flow may cause the WHPA to be partially mislocated resulting in areas that are actually contributing water to the well to end up outside the WHPA. This would result in a misconception of the actual sources of water for a well.

Variability and uncertainty in the direction of ambient ground-water flow may arise from several factors, including:

- No regional water-table map is available and the angle of ambient flow is based on an estimation from the topography of the land surface.
- The regional water-table map used is based on a limited number of simultaneous water-level measurements or the observation points are separated by large distances.
- Subjectivity in interpreting field data to construct a water-table map results in non-unique water-level contours.
- Subjectivity in estimating direction of hydraulic gradient from water-table maps.
- Temporal variations in the angle of ambient flow exist as a result of spatial or seasonal differences.

Table 2. Selection of input values for WHPA delineation.

DELINEATION DATA VARIABLES	FIRST SELECTION	SECOND SELECTION	THIRD SELECTION
Hydraulic Gradient	Calculated from regional water-table contour map in area up-gradient of the well, with gradient magnitude and direction calculated over distance of one mile[1]. Delineation to include angle of rotation calculated from site-specific data.	Calculated from regional water-table contour map in area up-gradient of the well, with gradient magnitude and direction calculated over distance of one mile[1]. Delineation to include +/-20 degree angle of rotation.	Gradient magnitude and direction based on topographic gradient and 0.5 conversion factor, in area up-gradient of the well[1]. Delineation to include +/-20 degree angle of rotation.
Aquifer Transmissivity	Adequate hydrologic tests from wells located within the modeled area[2].	Calculated as the product of hydraulic conductivity and aquifer thickness[3].	Estimated based on published values for comparable aquifers.
Effective Porosity	Adequate hydrologic tests from wells located within the modeled area[2].	Estimated based on total porosity and/or specific yield data from the aquifer.	Obtained from effective porosity values provided for selective aquifer types in table 1.
Aquifer Saturated Thickness	**For unconsolidated aquifers**, the vertical distance between the water table and the first significant confining layer underlying the aquifer in which the well is screened. **For bedrock aquifers**, the vertical distance between the water table and the bottom of the well, but no greater than 500 feet.	**For unconsolidated aquifers**, the vertical distance between the water table and the bottom of the well. **For bedrock aquifers**, the length of open borehole for the well, but not greater than 500 feet.	**For unconsolidated aquifers**, the average or median aquifer thickness for wells in this aquifer. **For bedrock aquifers**, the average or median aquifer thickness for wells in this aquifer.
Pumping Rate	For wells in production for at least two years, use the method below: Maximum average annual pumping rate during the period of operation, up to and including the previous 12 years, from actual pumping data, plus a 25% safety factor, but not more than the pump capacity and not less than 40% of pump capacity.	Estimated based on the method below yielding the lowest pumping rate: Installed pump capacity for the well. Water allocation for the individual well, if available. The planned maximum average annual pumping rate, over the next 12 years, if justified by the well owner to the satisfaction of the Department.	Estimated based on the number of connections serviced by the well, or the estimated population serviced by the well, with per-capita consumption at 100 gallons per day per capita, and occupancy based on census data for the specific municipality where the well is located. If the number of connections or the estimated population is not known, the average or median pumping rate for this type of well will be used.
Well Radius	One half the finished diameter of the well screen or open borehole listed on the well record.	One half the finished diameter of the well screen or open borehole listed on well construction diagram.	If unknown, use the radius corresponding to the well's pump capacity rate listed in Driscoll, 1986., Table 13.1, Ground Water and Wells, second edition.
Anisotropy (Ratio) and Direction	Value based on adequate hydrogeologic tests and analyses of wells within modeled area.	Value based on published values for the aquifer.	1:1 for all aquifers except the following: Mesozoic sedimentary rocks 10:1; Paleozoic sedimentary rocks 3:1. Direction is bedding plane strike from a published geologic map.

For all WHP methods, the first selection must be used if the data are available; if not available, the second selection must be used; and so on.
When site-specific values can not be determined from table it may be requested from the New Jersey Geological Survey, P.O. Box 427, Trenton, NJ 08625, or obtained from a published source or other source acceptable to the Department.

[1] If it is difficult to calculate the hydraulic gradient over a distance of one mile, due to rapid changes in the water-table gradient or direction, or due to the location of hydrologic boundaries, then the hydraulic gradient magnitude and direction should be calculated over an appropriate distance less than one mile.

[2] Tests must be adequate to permit accurate definition of hydrologic characteristics of the aquifer to the satisfaction of the Department.

[3] When calculating transmissivity, the hydraulic conductivity should generally be the geometric mean value for the aquifer as shown in table 3.

in ground-water recharge or unidentified pumping nearby.

Temporal variations in the direction of ground-water flow can be quantified at locations with sufficient regional water-level monitoring data. Such changes have been documented in published reports and have been identified as a primary cause of transverse dispersion of contaminant plumes.

To quantify expected temporal variation in hydraulic gradient directions in New Jersey aquifers, the NJGS evaluated eight sites in New Jersey with sufficient water-level monitoring data. The selected sites covered a variety of New Jersey aquifers, including coastal plain, bedrock and glacial aquifers. Mean hydraulic gradient directions and seasonal variations from the mean were calculated for numerous sampling points. A statistical analysis of the data showed that the total variation in the azimuth of the flow direction was as much as 48 degrees (24 degrees on either side of the mean) over a two year period. Based on this analysis, a 16.4-degree range on either side of the mean hydraulic gradient direction would sufficiently account for the variability resulting from temporal variation in hydraulic gradient direction at 90% of the sites.

To account for the variability in the accuracy of the selected angle of ambient flow, arising from both temporal variation and the other potential uncertainties listed above, a range of 20 degrees on either side of the selected angle of ambient flow will be used in delineating WHPA's. The variability associated with the angle of ambient flow will be factored into the WHPA delineation process by rotating the delineated WHPA, with the well as the pivot point, 20 degrees in both a clockwise and counter-clockwise direction. The total rotation will be 40 degrees. The entire area encompassed by the rotation is included in the WHPA. However, the rotated area should be truncated by appropriate hydrologic boundaries when such data are available. This 20-degree "angle of rotation" will be used for all WHPA delineations unless sufficient site-specific data justify the use of a smaller or larger angle of rotation or if the three-dimensional model method is used with the alternative described in item 5 of the Three-Dimensional Model Method section (page 12). The angle can be changed if sufficient evidence, covering the seasonal fluctuation phenomena, is presented as part of the delineation.

Calculation of a site-specific angle of rotation requires a network of observation wells acceptable to the Department, with a minimum of one year of quarterly water-level data, water-table maps, and calculated hydraulic gradient directions. The calculated site-specific angle of rotation will be equal to the total variation in the azimuth of ground-water flow directions observed in the data.

The NJGS has developed a computer program called "OUTPATH" that will apply the angle of rotation to outputs from the RESSQC version of the EPA WHPA model and create a file of the WHPA that can be incorporated into a geographic information system (GIS). It is available upon request from NJGS.

Transmissivity

Transmissivity is a measure of the quantity of water that an aquifer can transmit over its saturated thickness per unit width (that is, one foot) and a hydraulic gradient of one. In mathematical terms, transmissivity is equal to the product of the thickness and hydraulic conductivity of the aquifer.

For WHPA calculation, the aquifer's transmissivity will be selected based on adequate hydrologic tests from wells located within the modeled area. In areas where transmissivity values are not readily available, transmissivity should generally be obtained by multiplying the aquifer thickness by the geometric mean of hydraulic conductivity values measured in the aquifer of interest. Currently available hydraulic conductivity and transmissivity values for New Jersey aquifers are listed in tables 3 and 4. Where no data for a given formation or aquifer are available in tables 3 and 4, published values for similar aquifers may be used.

Effective Porosity

Porosity is important in ground-water hydrology because it tells us the maximum amount of water that an aquifer can contain when it is saturated. Porosity is the ratio of the volume of void spaces (that is, pores, or the space not occupied by solid matter) to the total volume of an aquifer. Porosity is expressed as a decimal fraction or as a percentage, such as 0.25 or 25%. Porosity in unconsolidated sand and gravel aquifers is derived from the spaces between grains. Porosity in consolidated bedrock aquifers (limestone, marble, shale, sandstone, granite and gneiss for example) is largely derived from fractures such as joints, faults, and other tabular openings along bedding planes. Only a part of this water is available to supply a well. A portion of an aquifer's overall porosity will not release or transmit water, due to the water being held in some pores by capillary tension, or because of dead-end pore space which does not transmit water to a well. This portion or percentage of pore space is called specific retention, because water is retained there and not released. Some clays have high specific retention (up to 48%), while sand, gravel and consolidated rock have low specific retention (ranging from less than 1% in solid rock to 3% in sand) (Heath, 1983). The portion of porosity that drains or transmits water under influence of gravity or due to pumping a well is called effective porosity. This is the percentage of the aquifer's pore space or storage available to supply a pumping well. Effective porosity is largest for sand and gravel (around 25%) and usually lowest for clay, silt, and bedrock (around 2%).

Of all the parameters necessary for delineating WHPA's, porosity and effective porosity is the most difficult to measure and quantify. The preferred method for quantifying effective porosity requires hydrologic tests at the well site, including pumping tests, material analysis, and tracer testing. For example, the effective porosity may be calculated based on its relationship with hydraulic conductivity (K), hydraulic gradient (i), and ground water velocity (v), in accordance with Darcy's Law, such that:

$$(n_e) = [K * i] / v$$

At present, there are few published values of effective porosity for aquifers in New Jersey. Ongoing research being conducted by the USGS and the NJGS should begin to fill this data gap. When detailed site-specific data or detailed aquifer specific data of porosity are not available, an effective porosity value will be obtained from the values provided in table 1 of this report. The values in table 1 were determined based on review of worldwide values of effective porosity from published sources including ground-water tracer tests conducted in the field and laboratory tests of aquifer materials. Effective porosity values for unconsolidated aquifers such as glacial stratified drift, and coastal plain aquifers, have been estimated to be 25% (table 1a). Effective porosity values for the rock aquifers of New Jersey, such as those in shale, limestone, sandstone, gneiss and granite, have been estimated to be 2% (table 1b). Due to the current lack of site-specific data, in developing WHPA's for public supply wells, NJGS exclusively used the effective porosity values noted in table 1a and 1b.

Table 3. Summary of horizontal conductivity (k) values for geologic and hydrogeologic units in New Jersey as of January 2002.

Geologic Unit	Number of tests	Arithmetic mean (ft/d)	Minimum (ft/d)	Maximum (ft/d)	Median (ft/d)	Standard deviation
Outwash deposits	1	177.00	177.00	177.00		
Deltaic sediment	1	59.00	59.00	59.00		
Fluvial over lacustrine sediment	1	110.00	110.00	110.00		
Till (Quaternary)	1	32.00	32.00	32.00		
Till (late Wisconsinan)	1	142.90	142.90	142.90		
Stratified drift	5	158.20	55.00	215.00	188.00	65.73
Glaciolacustrine sand and gravel	1	267.00	267.00	267.00		
Glaciolacustrine sand and gravel (late Wisconsinan)	1	285.00	285.00	285.00		
Glaciolacustrine sand and gravel (Illinoian)	1	28.00	28.00	28.00		
Cohansey Formation	11	125.25	52.00	216.00	116.70	55.73
Cohansey & Kirkwood Formations	5	152.20	98.00	200.00	160.00	48.07
Kirkwood Formation - lower member (sand facies)	5	110.60	22.00	334.00	57.00	126.86
Kirkwood Formation	4	179.00	80.00	365.00	135.50	127.63
Shark River Formation - Toms River member	1	32.00	32.00	32.00		
Mount Laurel Formation	1	41.00	41.00	41.00		
Mount Laurel and Wenonah Formations	3	12.17	7.00	20.50	9.00	7.29
Magothy, Raritan, and Potomac Formations	1	13.00	13.00	13.00		
Magothy Formation	6	119.85	19.00	314.00	66.90	116.73
Raritan Formation	2	72.90	71.60	74.20	72.90	1.84
Potomac Formation	1	49.00	49.00	49.00		
Potomac Formation, Unit 3 (upper subsurface)	1	153.00	153.00	153.00		
Brunswick Group (Passaic Formation through Boonton Formation)	1	0.54	0.54	0.54		
Towaco Formation	1	5.00	5.00	5.00		
Passaic Formation	1	2.51	2.51	2.51		
Leithsville Formation	1	21.00	21.00	21.00		
Leithsville Formation and Hardyston quartzite, undivided	1	13.50	13.50	13.50		
late Proterozoic rocks, undifferentiated	1	0.05	0.05	0.05		
Hornblende granite	1	0.51	0.51	0.51		
Pyroxene granite	1	0.58	0.58	0.58		
Hydrogeologic unit	**Number of tests**	**Arithmetic mean (ft/d)**	**Minimum (ft/d)**	**Maximum (ft/d)**	**Media (ft/d)**	**Standard deviation**
continous or discontinous till	2	87.45	32.00	142.90	87.45	78.42
glacial sand and gravel	11	156.09	28.00	285.00	177.00	86.38
Cohansey aquifer	1	216.00	216.00	216.00		
Kirkwood-Cohansey water-table aquifer system	16	129.80	52.00	200.00	133.89	49.12
Rio Grande water-bearing zone	3	187.33	80.00	365.00	117.00	154.97
Atlantic City "800-foot" sand aquifer	5	110.60	22.00	334.00	57.00	126.86
Piney Point aquifer	1	32.00	32.00	32.00		
Mount Laurel-Wenonah aquifer	4	19.38	7.00	41.00	14.75	15.60
Potomac-Raritan-Magothy aquifer system	1	13.00	13.00	13.00		
upper Potomac-Raritan-Magothy aquifer	6	119.85	19.00	314.00	66.90	116.73
middle Potomac-Raritan-Magothy aquifer	2	72.90	71.60	74.20	72.90	1.84
lower Potomac-Raritan-Magothy aquifer	2	101.00	49.00	153.00	101.00	73.54
Brunswick aquifer	3	2.68	0.54	5.00	2.51	2.24
Jacksonburg limestone, Kittatinny Supergroup and Hardyston quartzite	2	17.25	13.50	21.00	17.25	5.30
igneous and metamorphic rocks	3	0.38	0.05	0.58	0.51	0.29
Not all aquifers in New Jersey are represented on table 3, because some have not been tested or analyzed.						

Table 4. Summary of transmissivity values for geologic and hydrogeologic units in New Jersey as of January 2002.

Geologic Unit	Number of tests	Arithmetic mean (ft²/d)	Minimum (ft²/d)	Maximum (ft²/d)	Median (ft²/d)	Standard deviation
Deltaic sediment	1	1070	1070	1070		
Fluvial over lacustrine sediment	1	7142	7142	7142		
Stratified drift	5	10528	6802	15444	10070	3133
Glaciolacustrine sand and gravel (late Wisconsinan)	1	17511	17511	17511		
Glaciolacustrine sand and gravel (Illinoian)	1	2642	2642	2642		
Cape May Formation	1	1312	1312	1312		
Cohansey Formation	11	8907	3102	18499	7794	4250
Cohansey & Kirkwood Formations	7	14264	6858	24902	11256	6999
Kirkwood Formation - lower member (sand facies)	6	7351	1792	16690	5847	5022
Kirkwood Formation	6	11630	2354	38475	7007	13560
Shark River Formation - Toms River member	2	1339	442	2235	1339	1268
Vincentown Formation	1	2286	2286	2286		
Mount Laurel Formation	1	2050	2050	2050		
Mount Laurel and Wenonah Formations	3	849	633	1232	683	332
Englishtown Formation	3	1122	426	1932	1008	759
Magothy, Raritan, and Potomac Formations	1	2593	2593	2593		
Magothy Formation	9	7302	1175	22956	3050	8492
Magothy Formation - Old Bridge Sand member	1	1710	1710	1710		
Raritan Formation	3	4621	2597	8307	2960	3197
Raritan Formation - Farrington Sand member	3	12103	2803	21599	11907	9400
Potomac Formation	1	1957	1957	1957		
Potomac Formation, Unit 3 (upper subsurface)	1	7969	7969	7969		
Brunswick Group (Passaic Formation through Boonton Formation)	1	136	136	136		
Towaco Formation	2	889	583	1195	889	433
Passaic Formation	8	573	45	1375	477	453
Rickenback dolomite	1	19254	19254	19254		
Rickenback dolomite - lower member	1	127	127	127		
Allentown dolomite	1	75	75	75		
Leithsville Formation	4	2993	1041	6498	2216	2425
Leithsville Formation - Walkill member	1	274	274	274		
Leithsville Formation and Hardyston quartzite, undivided	1	1184	1184	1184		
late Proterozoic rocks, unifferentiated	1	14	14	14		
Hornblende granite	1	100	100	100		
Pyroxene granite	2	110	36	183	110	104
Hypersthene-quartz-plagioclase gneiss	2	126	95	157	126	44
Hydrogeologic unit	**Number of tests**	**Arithmetic mean (ft²/d)**	**Minimum (ft²/d)**	**Maximum (ft²/d)**	**Median (ft²/d)**	**Standard deviation**
glacial sand and gravel	9	9001	1070	17511	5363	9560
Holly Beach water-bearing zone	1	1312	1312	1312		
Cohansey aquifer	1	12505	12505	12505		
Kirkwood-Cohansey water-table aquifer system	19	12023	3102	38475	8726	8796
Rio Grande water-bearing zone	3	8101	3994	10941	3643	9369
Atlantic City "800-foot" sand aquifer	7	6637	1792	16690	4958	5744
Piney Point aquifer	2	1339	442	2235	1268	1339
Vincentown aquifer	1	2286	2286	2286		
Mount Laurel-Wenonah aquifer	4	1150	633	2050	659	958
Englishtown aquifer system	3	1122	426	1932	759	1008
Potomac-Raritan-Magothy aquifer system	1	2593	2593	2593		

Table 4 (continued). Summary of transmissivity values for geologic and hydrogeologic units in New Jersey as of January 2002.

Geologic Unit	Number of tests	Arithmetic mean (ft²/d)	Minimum (ft²/d)	Maximum (ft²/d)	Median (ft²/d)	Standard deviation
upper Potomac-Raritan-Magothy aquifer	10	6743	1175	22956	8199	2655
middle Potomac-Raritan-Magothy aquifer	6	8362	2597	21599	7498	5634
lower Potomac-Raritan-Magothy aquifer	2	4963	1957	7969	4251	4963
Brunswick aquifer	11	591	45	1375	449	583
Jacksonburg limestone, Kittatinny Supergroup and Hardyston quartzite	9	3654	75	19254	6180	1184
igneous and metamorphic rocks	6	98	14	183	66	98

Not all aquifers in New Jersey are represented on this table, because some have not been tested and analyzed.

Aquifer Thickness

The thickness of an aquifer is defined as the vertical distance between its upper and lower physical boundaries. Determining aquifer thickness for purposes of calculating a WHPA, then, requires determining the locations of the upper and lower boundaries of the aquifer.

Because well head protection is primarily concerned with travel times in water-table aquifers, the water table constitutes the upper boundary of the aquifer. Using well logs or other site-specific information, the lower boundary of a water-table aquifer is described by the first significant confining unit underlying the aquifer. The degree to which this lower boundary can be defined will differ for unconsolidated granular aquifers and bedrock aquifers. For unconsolidated aquifers, the first significant confining layer underlying the pumping well will usually consist of a significant stratigraphic layer consisting of silt and/or clay, or in the case of glacial valley-fill aquifers, relatively impervious bedrock underlying the aquifer. When site-specific data on the location of confining units are not available, the NJGS can be contacted for the best available data in the area, or published sources such as the "Hydrogeologic Framework of the New Jersey Coastal Plain" (Zapecza, 1989) may be used. Therefore, aquifer thickness in unconsolidated aquifers will be the calculated vertical distance between the water table and the first significant confining layer underlying the well.

In bedrock aquifers, the bottom of the aquifer is not so easily described. The lower boundary of a bedrock aquifer coincides with the depth at which water-bearing fractures cease to occur, or with an underlying impervious bedrock stratum. Since information on the depth to which fractures occur is not always readily available, for purposes of calculating WHPA's, the lower boundary of bedrock aquifers will be defined as the depth of the open well borehole. A limit of 500 feet will be applied in assigning the thickness of bedrock aquifers. This limitation is generally consistent with data on well depths and occurrence of water-bearing fractures of wells in New Jersey. In bedrock aquifers, aquifer thickness will be the measured vertical distance between the water table and the bottom of the open borehole, with total aquifer thickness not exceeding 500 feet.

Where insufficient geologic and/or hydrogeologic data exits, aquifer thickness will be estimated using the methods listed in table 2 of this report, which are described below. Preference is given to methods that come closest to approximating the true aquifer thickness. For example, in unconsolidated aquifers the second option for assigning aquifer thickness will be the measured or published vertical distance between the water table and the bottom of the well. For bedrock aquifers, the length of the open borehole may be used to define aquifer thickness. Where information on a well is scarce, aquifer thickness will be defined as the average or median aquifer thickness from wells with known aquifer thickness in the same aquifer. See table 5 for average well depth for selected aquifers in New Jersey.

Table 5. Average depth of unconfined, public-supply wells in selected aquifers.

Aquifer Name	Number of Public Supply Wells	Average Depth (in feet)
Glacial Sand and gravel	252	100
Holly Beach water bearing zone	12	60
Kirkwood-Cohansey	433	120
Vincentown	8	130
Upper Potomac Raritan Magothy (PRM)	60	100
Middle PRM	54	230
Lower PRM	62	210
Brunswick	400	330
Basalt (Jurassic)	15	300
Stockton	33	340
Rocks of the Green Pond Mtn. Region, Kittatiny Mtn., and Minisink Valley	20	250
Martinsburg and Jutland Sequence	9	310
Jacksonburg Limestone, Kittatiny Supergroup and Hardyston Quartzite	72	280
Igneous and Metamorphic Rocks	212	310

Pumping Rate

The pumping rate is a measure of the quantity of water withdrawn, or expected to be withdrawn, from a well over a given time period. Pumping rate is usually expressed as gallons per minute, million gallons per day, or cubic feet per day.

The first step in selecting the pumping rates will be to determine if the well has been in production for at least two years, and if withdrawal data for the well are available in the Site Specific Water Use Data System maintained by the N. J. Geological Survey. If data are available, the pumping rate will be based on the preferred selection method which requires an evaluation of existing data for the well's period of operation, up to and including the previous 12 years. The 12-year time frame was selected based on the 12-year Time of Travel for Tier 3 and the availability of accurate historical pumping data. The following steps will be taken:

1) For each year of data, the total withdrawal will be determined;

2) An average annual pumping rate will be determined for each year's data by dividing the total withdrawal, in each year, by the number of minutes in a year (525,600).

3) The average annual pumping rate from the year with the highest average annual pumping rate will be selected as the maximum average annual pumping rate;

4) The maximum average annual pumping rate will be increased by a safety factor equal to 25% of the maximum average annual pumping rate;

5) If the maximum average annual pumping rate plus the safety factor results in a value that is greater than 40% of the well's pump capacity, then it will be used as the pumping rate in the delineation of the WHPA. If the maximum average annual pumping rate plus the safety factor results in a value that is less than 40% of the well's pump capacity, then 40% of pump capacity will be used as the value for pumping rate in the delineation of the WHPA.

6) If the maximum average annual pumping rate plus the safety factor results in a value that is greater than the well's pump capacity, then the pump capacity value or the maximum average annual pumping rate (without the safety factor), whichever is greater, will be used as the value for pumping rate in the delineation of the WHPA.

If the well is new, has not been in production for at least two years, or does not have actual withdrawal data available, the pumping rates will be selected from the following method yielding the lowest pumping rate:

1) Installed pump capacity for the well.

2) Permitted allocation of water for the individual well, if available.

3) The planned maximum average annual pumping rate, over the next 12 years, if justified by the well owner to the satisfaction of the Department.

If the data are insufficient to obtain pumping rates from the above described methods, the pumping rates will be estimated based on the number of connections or the estimated population serviced by the well, with per-capita consumption at 100 gallons per-capita per day and occupancy based on census data for the municipality in which the well is located.

If the number of connections or the estimated population is not known, an average or median pumping rate for this type of well will be used.

Well Radius

Some delineation methods require a value for well radius. Well radius is one half the finished diameter of the well screen or open borehole extending over the water producing interval of the well. The well record is the preferred source for obtaining this value. In instances where the well record does not exist, well radius will be obtained from the well construction diagram of the well. If neither of these two sources exist, well radius will be selected based on the well's pump capacity in accordance with Ground Water And Wells, table 13.1, "Recommended Well Diameters for Various Pumping Rates". If the pump capacity is not available either, then the pumping rate used in the delineation will be used to select the well radius using Ground Water and Wells, table 13.1 (Driscoll, 1986).

Anisotropy

Anisotropy refers to the directionally dependent movement of ground water in an aquifer. Anisotropy arises from the orientation and spatial distribution of conductive features such as fractures, solution openings, and primary porosity (intergranular) within the aquifer. In the case of New Jersey's bedrock aquifers, numerous aquifer tests and ground-water contaminant studies demonstrate anisotropic ground-water movement (Herpers and Barksdale, 1951, Nichols, 1968, Vecchioli, 1969, Spayd, 1986, USGS, 1997, and Nicholson and Watt, 1998). These studies have described anisotropic behavior in bedrock with ground-water flowing preferentially in the direction of bedding strike.

Based on these findings, it is reasonable to expect PCWS wells to exert greater impact and more extensive capture of ground water in the direction of bedding strike. For all WHPA's located in Paleozoic and Mesozoic sedimentary rock aquifers, NJGS assigned preferential flow direction and an anisotropy ratio. In most cases, the preferential flow direction is bedding strike and in a few cases, the preferential direction is the strike of a major fault from which the well appears to be obtaining water. The strike of bedding and faults were taken from published geologic maps. For the Paleozoic bedrock aquifers, an anisotropy ratio of 3:1 was used and in the Mesozoic sedimentary rock aquifers, the assigned anisotropy ratio was 10:1. Anisotropy ratio is the ratio of the aquifers greatest transmissivity (parallel to the preferred flow direction) to the least transmissivity (perpendicular to the preferred flow direction)

Submission of Delineations

Any person interested in submitting a WHPA to the Department will be required to include the following information:

1. Applicant name, address and telephone number.

2. Well owner name, address, and telephone number.

3. Person(s) performing the delineation and their professional qualifications, company names, address and telephone number.

4. Department permit numbers including, where applicable, the public water system identification number (PWSID), State well permit number, water allocation permit number, well and well-field name (if used), and water use registration number.

5. The WHPA delineations should be submitted in digital format compatible with the Department's GIS and in accordance with the Department's Digital Data Standards. These standards are found on the web at the following address: www.state.nj.us/dep/gis. Conformance with the digital standards will ensure positional accuracy and compatibility to the NJDEP GIS system. WHPA's are stored and managed on this system. In addition, the applicant may submit a mylar overlay of the orthophoto quadrangle map(s) at a scale of 1:24,000 or 1:12,000 showing the well location, well permit number clearly labeled, and the three tiers of the WHPA. The overlay must be drawn in accordance with the delineation mapping requirements section and the digital data standards above.

6. Additional mylar overlays when submited shall be referenced to the map required in item number 5 above to clearly show any physical features, water level elevations and contours, hydrologic boundaries, model grid, and all other wells or data points in the area used in determining the WHPA, as applicable. The overlays will be drawn in accordance with the delineation mapping requirements section.

7. Date of well construction, record of the well's construction, depth of the well, well screen or open-hole location, and other well and aquifer attributes as required for the delineation process, including the method used to locate the well. Sources of information must be documented. Parameters should be reported in consistent units, English or metric, and should be those commonly reported in scientific literature, and identified within the report.

8. All data, equations, derived values, and name of any models used for the delineation process must be included in the submission via electronic media compatible to the Department's GIS and digital data standards referenced above

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The WHPA delineation data should be sent to the Bureau of Safe Drinking Water, P.O. Box 426, Trenton, NJ 08625.

Delineations, which are completed by the Department, will be submitted for public review within the Department's SWAP Program.
The Department will maintain and make available to the public the WHPA delineations. The Department intends to make the maps available to the public in a digital form, in conformance with the Department's GIS and showing, at a minimum, the well location, well permit number and the three tiers of the WHPA delineation. They are available on the web at: http://www.state.nj.us/dep/njgs/.

Delineation Mapping Requirements

The requirement to submit a mapped WHPA pertains only to those parties volunteering to perform a delineation outside of the Safe Drinking Water permitting process. The Department will perform delineations on all public wells. This section is designed to provide easy review of submitted material while maintaining an accuracy standard of plus or minus 50 feet. The recommended method for submitting WHPA delineations is a digital format compatible with the Department's GIS and Digital Data Standards. The digital version may be accompanied by a hard copy on mylar. Mylar provides the best medium for mapping in terms of accuracy, media stability, and for the purpose of review for an overlay. Therefore, the hard copy, if submitted, of the WHPA delineation is required on a mylar medium.

The maps required for the delineation, along with the data, will speed the review process. It is anticipated that all WHPA delineations along with their pertinent attributes will be placed into a computer database and transferred to the GIS. Submitted data will be reviewed for inconsistencies. Therefore, it is important that data including the WHPA delineation be received in digital format. Digital data should meet the Department's Mapping and Digital Data Standards (NJDEP, 1998). This will facilitate Department review and placement into the Department's GIS.

Well-location accuracy is essential to the delineation process. Well-location error may cause areas to be inappropriately placed under stricter controls than necessary, or conversely to not be included in the WHPA when they should. This required the Department to determine which available method or methods would provide the best accuracy. Methods in which the best accuracy could be obtained were assessed with consideration given to the cost of determining the well location and a reasonable level of technology, which would provide the best accuracy. Two methods were determined to provide an accuracy of plus or minus 50 feet or less. These are:

1) Global Positioning System = with a maximum error of approximately 40 feet to a minimum of three feet, using differential correction of field data.

2) Surveying location to the tenth of a second = 12.8 feet or other surveying technique which provides results within the accuracy limit.

The outer boundary line width of the WHPA corresponds to approximately 24 feet on the ground, using a ball point pen on paper at a scale of 1:24,000. It was decided based on best available technology, that this line would represent the boundary line of the WHPA. Due to the resolution of the well location, WHPA delineations are considered to have an accuracy of plus or minus 50 feet in any direction from the mapped location. In considering all the locational limitations, it was decided that any pollutant source located within or on the boundary of the WHPA will be assumed to be located inside of the WHPA, unless shown otherwise through more accurate well location, WHPA delineation or mapping technique.

The Department has field-located all existing CWS wells, using GPS, as part of its WHPA delineation process. NCWS wells have been field located mostly by the counties and New Jersey Water Association using GPS methods as well.

All maps and digital information must be referenced to the NAD83 geodetic datum.

All maps should have a minimum of four reference points corresponding to the quadrangle tic marks. The coordinates for each tic should be listed by the appropriate tic mark and should be in New Jersey State Plane Feet. Tic marks should be referenced to a mylar orthophoto quadrangle map at a 1:24,000 or 1:12,000 scale. Proper identification for the base map should be provided in the lower right hand corner of the WHPA delineation map.

Maps should not be crowded and care should be taken not to obscure the clarity of data or any features.

Information from other sources should be accurately transferred to either the WHPA mylar or the accompanying features map.

When WHPA delineation is submitted on mylar, delineations should be made with a standard drafting/technical pen producing a line width of no greater than 0.02 inches. In all cases, the well symbols, drafted lines and points should bisect the feature as seen on the base map and must be within 50 feet of its true location.

The name and affiliation of the preparer of the map, the date of preparation, the scale or scales employed, a north arrow, and the source of data used should be stated in a legend block on each map.

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Glossary

Applicant- A person or persons not affiliated with the Department of Environmental Protection who submits or intends to submit a Well Head Protection Area delineation for review and approval.

Anisotropy- The condition of aquifer properties that vary by direction.

Aquifer- A saturated geologic formation, group of formations, or part of a formation which is sufficiently permeable to transmit water to a pumping well or spring in usable and economic quantities. The water table of an unconfined aquifer may vary over time; "aquifer" applies to the full-saturated zone at any time.

Calculated fixed radius (CFR) -The method of describing an aquifer volume around a well in plan view (mapped on the land surface) by a cylinder, using the pumping rate of a well and the storage of water in an aquifer, over a specific pumping time, such that the ground water within the cylinder equals the volume of water pumped by the well.

Confined aquifer- An aquifer which contains ground water under pressure between or below confining unit(s) so that the water surface rises above the top of the aquifer in a tightly-cased well which derives its water from the aquifer.

Confining unit – A body of relatively impermeable material that is above or below one or more aquifers, restricting the flow of water to or from an aquifer or aquifers.

Department – The New Jersey Department of Environmental Protection.

Ground water - The portion of water beneath the land surface that is within the saturated zone.

Hydrologic boundary - Hydrologic or geologic features which form a deterrent to ground-water flow, intercept ground-water flow, or provide a large, continuous source of ground-water flow. These boundaries may include but are not limited to drainage divides, geologic formations, geologic structures, and surface water bodies.

Community water system (CWS) - A public water system that serves at least 15 service connections used by year-round residents or regularly serves at least 25 year-round residents.

Non-community water system (NCWS) -a public water system that is not a CWS and which serves at least 15 service connections or regularly serves at least 25 individuals more than 60 days of the year.

Public water system - A system for the provision to the public of piped water for human consumption, if such system has at least 15 service connections or regularly serves at least 25 individuals.

Qualified ground-water professional – Any person who has received a baccalaureate or post-graduate degree in hydrogeology, geohydrology, geology, engineering or soil science and has five years of appropriate professional experience in ground-water hydrology. This definition has been modified from the final USEPA municipal solid waste landfill rules published in the Federal Register, October 9, 1991 [40 CFR Section 258.50(f)]. This term has been so defined to focus on the appropriate education and professional experience relevant to the aspects of ground-water modeling required to perform zone of contribution analysis for water-supply wells. Applicants submitting advanced delineations requiring ground-water modeling and ground-water professionals are recommended to submit evidence of their professional credentials.

Regional hydraulic gradient – The change in head, per unit of distance, in a specified direction, within a specified region.

Saturated zone – The subsurface zone in which all the subsurface pores in the rock or soil are filled with water at a pressure greater than or equal to atmospheric.

SWAP - Source Water Assessment Program established and implemented under 1996 Amendments to federal Safe Drinking Water Act (P.L.104-182) and described in the USEPA approved New Jersey Source Water Assessment Program Plan, November 1999.

Time of travel (TOT) - The average time that particles of water will take to travel in the saturated zone from a given point to a pumping well.

Unconfined aquifer - An aquifer in which the water table forms the upper boundary and a confining unit forms the lower boundary.

Water table - The top surface of the saturated zone in an unconfined aquifer, which is under atmospheric pressure.

Well head – The well borehole and related equipment.

Well Head Protection Area (WHPA) - An aquifer area described in plan view around a well, from within which ground water is reasonably likely to flow to the well and through which ground-water pollution, if it occurs, is reasonably likely to pose a significant threat to the water quality of the well. The WHPA is delimited by the use of a time-of-travel, and hydrologic boundaries, and is further subdivided by multiple times of travel.

WHP - Well head protection.

WHPP – The Well Head Protection Program established pursuant to Section 1428 of the Federal Safe Drinking Water Act, P.L. 93-523, 42 USC 300 et. seq. and described within the New Jersey Well Head Protection Program Plan (NJDEP, 1991) and subsequent documents.

Zone of contribution – The portion of an aquifer surrounding a pumping well that encompasses all areas or features that supply ground water or ground-water recharge to the well over time.