

DEPARTMENT OF ENVIRONMENTAL PROTECTION
Bureau of Safe Drinking Water

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TITLE: Aquifer Testing Guidance for Public Water Systems

EFFECTIVE DATE: April 12, 2014

AUTHORITY: Pennsylvania's Safe Drinking Water Act (35 P.S. § 721.1 *et seq.*), and regulations at 25 Pa. Code Chapter 109

POLICY: Department of Environmental Protection (DEP) staff will follow the guidance and procedures presented in this document to support implementation of permitting and approval activities for new or expanded public water systems (PWSs) under the Drinking Water Management Program.

PURPOSE: This guidance document establishes the guidelines for aquifer testing for new or expanded PWSs. Information provided in this guidance replaces the corresponding procedures included in Part II of the Public Water Supply Manual pertaining to aquifer testing guidance.

APPLICABILITY: This guidance will apply to all new or expanded PWSs that require a construction permit and for all noncommunity water systems (NCWSs) that have a proposed groundwater withdrawal rate greater than 100,000 gallons per day (gpd).

DISCLAIMER: The policies and procedures outlined in this guidance document are intended to supplement existing requirements. Nothing in the policies or procedures shall affect regulatory requirements.

The policies and procedures herein are not an adjudication or a regulation. There is no intent on the part of DEP to give these rules that weight or deference. This document establishes the framework within which DEP will exercise its administrative discretion in the future. DEP reserves the discretion to deviate from this policy statement if circumstances warrant.

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List of Acronyms

CSL – Clean Streams Law

CWS – Community Water System

DEP – Department of Environmental Protection

DRBC – Delaware River Basin Commission

EHB – Environmental Hearing Board

EPA – United States Environmental Protection Agency

gpd – Gallons per Day

gpm – Gallons per Minute

MPA – Microscopic Particulate Analysis

NTNCWS – Nontransient Noncommunity Water System

PNDI – Pennsylvania Natural Diversity Inventory

PWS – Public Water System

SDWA – Safe Drinking Water Act

SRBC – Susquehanna River Basin Commission

SWIP – Surface Water Identification Protocol

USGS – United States Geological Survey

ZOI – Zone of Influence

I. Introduction

This guidance document outlines the procedures for conducting an aquifer test for new or expanded public water systems (PWSs) that intend to utilize groundwater sources. An aquifer test should be conducted for all PWSs that are required to obtain a construction permit in accordance with the requirements of 25 Pa. Code Chapter 109. This includes all community water systems (CWSs) and noncommunity water systems (NCWSs) that do not meet the permit exemption requirements under Section 109.505 of the regulations. Additionally, this guidance applies to NCWSs that have a proposed groundwater withdrawal rate greater than 100,000 gallons per day (gpd). It is imperative that the water supplier be in close contact with the appropriate DEP regional office during all phases of a groundwater withdrawal project.

II. Regulatory Authority

A. Department of Environmental Protection

The DEP is authorized to issue permits to PWSs under its Safe Drinking Water Program pursuant to the Pennsylvania Safe Drinking Water Act (SDWA) (35 P.S. § 721.1 *et seq.*) and 25 Pa. Code Chapter 109. When groundwater is utilized as the source, an evaluation of the safe yield of the aquifer is necessary for all PWSs. The safe yield is the amount of water that can be withdrawn from an aquifer without causing an undesired result, such as adverse dewatering of an aquifer, induced potential health threats or impacts upon stream uses. Pursuant to 25 Pa. Code § 109.503(a)(1)(iii)(C), the application for a construction permit must include the following:

An evaluation of the quantity of the raw water from each new source....
Aquifer test data, including drawdown and recovery data and the derivation of hydraulic conductivity, transmissivity and storage coefficient of the aquifer, shall be submitted for wells....The Department may require that other information be submitted to evaluate the safe yield of the source.

For NCWSs that do not require a permit, DEP is authorized to issue approvals under its Safe Drinking Water Program. Pursuant to 25 Pa. Code § 109.505, all NCWSs that require DEP approval must adequately characterize the quality of the proposed source. For proposed groundwater withdrawal rates in excess of 100,000 gpd, an aquifer test is sufficient for characterizing groundwater quality when the aquifer is stressed under pumping conditions.

Finally, Section 7(j) of the SDWA provides that DEP may issue a permit if it determines that the proposed water system, among other things, complies with other laws administered by DEP.

B. River Basin Commissions

The Delaware River Basin Commission (DRBC) and the Susquehanna River Basin Commission (SRBC) require project review and approval for certain groundwater withdrawal projects. The DRBC and the SRBC requirements are outlined at 18 CFR Parts 410 (DRBC) and 806 (SRBC), respectively. The water supplier should contact the

appropriate river basin commission prior to project development. As necessary, DEP routinely coordinates its activities closely with the appropriate river basin commission during all phases of a groundwater withdrawal project.

III. Permitting or Approval Process for Groundwater Sources

An efficient process for permitting or approving groundwater sources is promoted through following appropriate procedures. Components of the permitting or approval process include the following: a preliminary conference, well siting, a site survey, a pre-drilling plan, well drilling, an aquifer test monitoring plan, aquifer testing and submission of a hydrogeologic report with other components of the permit or approval application. All hydrogeologic work activities associated with the project should be conducted by a registered professional geologist licensed by the Commonwealth of Pennsylvania (hereinafter, the professional geologist).

A. Preliminary Conference

A meeting between the water supplier, the professional geologist and the DEP promotes a smooth process for permitting or approving a PWS construction permit application or approval form. The meeting should be conducted prior to well siting. This will provide the water supplier and the professional geologist with a better understanding of the information needed to complete a detailed hydrogeologic report for the proposed groundwater source.

B. Production Well Siting

The water supplier and their professional geologist are responsible for siting the production well (the proposed water supply well) at an appropriate location and should make reasonable efforts to obtain the highest quality groundwater sources available. It is important that the hydrogeologic setting be considered during the well siting phase of a project.

The location of the production well should be adequate to protect the groundwater source from foreseeable sources of contamination, and reasonable measures should be taken to prevent diminution of source water quality. The well should be located so that it is protected against natural disasters, such as floods, fires, earthquakes, etc. Well location should also be based on consistency with the Pennsylvania Natural Diversity Inventory (PNDI) guidelines which are outlined in DEP's document, *Policy for Pennsylvania Natural Diversity Inventory (PNDI) Coordination During Permit Review and Evaluation*, DEP ID: 021-0200-001.

If groundwater withdrawal has potential to impact a special protection water (High Quality or Exceptional Value) based on designated use classification per 25 Pa. Code Chapter 93, the water supplier should work with DEP in creating a plan that satisfies the guidelines outlined in DEP's guidance, *Water Quality Antidegradation Implementation Guidance*, DEP ID: 391-0300-002.

The Zone I wellhead protection area is the protective zone immediately surrounding a well, spring or infiltration gallery which is a 100-to-400-foot radius depending on site-specific source and aquifer characteristics. For CWSs, the production well should be

sited so the Zone I wellhead protection area can be substantially controlled by the owner of the PWS.

C. Site Survey

After the well is sited, locational data (latitude and longitude) should be provided to DEP so a site survey can be conducted. DEP will conduct the site survey and evaluate the well location to survey and document the physical surroundings of the well and its proximity to any potential sources of contamination.

D. Pre-Drilling Plan

After the site survey is conducted, the professional geologist should prepare and submit a pre-drilling plan to the appropriate DEP regional office. The plan should establish a preliminary hydrogeologic understanding of the project site, a preliminary monitoring plan for aquifer testing and the proposed well construction design of the production well(s). Well drilling should not commence until the pre-drilling plan is approved by a DEP regional hydrogeologist. For existing wells being proposed as a source of public water supply, a plan should be submitted to DEP prior to aquifer testing. Components of the pre-drilling plan are included in Appendix A.

E. Well Drilling

After DEP approval of the pre-drilling plan, the production well(s) and monitoring wells should be drilled by a registered well driller licensed by the Commonwealth of Pennsylvania. The DEP should be provided with dates and times of all drilling and grouting activities.

Erosion and sediment control measures should be followed for all earth moving activities. See 25 Pa. Code Chapter 102 and DEP's guidance document, *Erosion and Sediment Pollution Control Manual*, DEP ID: 363-2134-008 for further information.

F. Pre-Drilling Plan Modifications

After well drilling, the professional geologist should provide DEP with any modifications to the initial pre-drilling plan in an addendum to the pre-drilling plan. Aquifer testing should not commence until the addendum is approved by the DEP hydrogeologist. Appendix A provides an outline of some common pre-drilling plan modifications that may result from well drilling.

G. Aquifer Testing

In accordance with 25 Pa. Code Chapter 109, a properly designed aquifer test should be conducted on any well(s) proposed as a new source in order to adequately define the hydraulic characteristics of the aquifer and well(s). Data from the test is subject to appropriate analysis to demonstrate the suitability of the well as a long-term source of public drinking water including, when necessary, the evaluation of significant potential impacts from the groundwater withdrawal on other water resources. The results derived from properly conducted and analyzed aquifer tests will also provide water suppliers with

the data necessary to support informed decision making on water supply management and planning issues.

H. Hydrogeologic Report Submission and Approval

Data and interpretations are needed to properly evaluate the safe yield of a proposed groundwater source. As such, all data and associated interpretations generated during the pre-drilling and aquifer testing phases of the project should be synthesized in a hydrogeologic report. The report should be prepared by the professional geologist and submitted to DEP as part of the PWS construction permit application. For NCWSs, where a construction permit application is not required, the report should be submitted with the *PWS Inventory and Brief Description Form*, DEP ID: 3900-FM-BSDW0033. A PWS cannot operate the proposed groundwater source until a construction and operating permit has been issued or an approval granted by DEP.

IV. Aquifer Test Design

Proper test design implies that sufficient planning is undertaken to ensure that the test will provide acceptable results for the anticipated site conditions. A conceptual understanding of the hydrogeologic setting along with the identification of potentially impacted water resources are key components for aquifer test design, execution and analysis. Aquifer test design and the conceptual understanding should be considered when developing the pre-drilling plan and modified accordingly as more site-specific data become available.

A. Hydrogeologic Setting

A hydrogeologic conceptual model serves as an illustrative delineation and formulation of the controlling aspects of groundwater flow from the recharge area to the discharge area. Information necessary to develop a conceptual model includes the lithology, depth, thickness, position, extent and structural trends of the water-bearing formations and confining strata; nature and location of hydrologic boundaries; groundwater flow direction; the regional hydrogeologic framework; and topography. Risser and Barton, 1995 and Appendix B highlight some important questions to consider for developing a representative conceptual model.

Hydrogeologic and topographic cross sections along with delineations of the area of diversion and the contributing area are useful tools for illustrating the hydrogeologic setting around the production well. The area of diversion (the Zone II wellhead protection area) is the surface area of the aquifer that has the same horizontal extent as the volume through which water is diverted to the well (Brown, 1963). The Zone II wellhead protection area is a 1/2 mile radius around the well unless a more detailed delineation is conducted. The contributing area surrounding the production well is the area of diversion and any adjacent surface areas that provide recharge to the aquifer through which water is diverted to the well (Risser and Barton, 1995). The Zone II wellhead protection area and Zone III, if present, comprise the contributing area for the water sources. The area of diversion and the contributing area are impacted by the hydrogeologic setting and other groundwater withdrawals (well interference). Delineation methodologies for fractured bedrock and unconsolidated hydrogeologic settings are provided in Risser and Barton, 1995 and Risser and Madden, 1994,

respectively. Additional information outlining the concept of a contributing area around a production well is provided in Morrissey, 1987 and US EPA, 1987.

B. Potentially Impacted Water Resources

Aquifer test design should also consider potential impacts from groundwater withdrawal on other water resources. To assure compliance with the Clean Streams Law (CSL), adjacent water resources may need to be monitored during aquifer testing. As a starting point, water resources located within the estimated area of diversion should be established as monitoring points. In general, if a water resource is not located within this area monitoring is unnecessary. High permeability flow paths can exist in karst and highly weathered bedrock settings. As a result, water resources may need to be monitored within the estimated contributing area. The water supplier and the professional geologist should work closely with the DEP regional hydrogeologist where circumstances warrant.

V. Well Construction and Test Pump

A. Well Construction

A properly installed and functional production well and monitoring wells are necessary for a successful aquifer test. Detailed well logs of construction and hydrogeologic characteristics should be recorded in the field by trained staff during all drilling activities.

To improve hydraulic efficiency of the wells, appropriate well development techniques should be utilized to remove fine-grained material from the well. Well development methodologies are outlined in Chapter 2 of DEP's *Groundwater Monitoring Guidance Manual*, DEP ID: 383-3000-001.

1. Production Well

All production wells should be constructed in accordance with the standards outlined in the General Well Construction Section (Section III) of Part II of DEP's *Public Water Supply Manual*, DEP ID: 383-2125-108. Borehole camera or video imaging logs of the production well may be beneficial to assure appropriate well construction and provide additional information on soil, rock and groundwater characteristics.

2. Monitoring Well

Monitoring wells should be located and constructed to provide the controlled access necessary to characterize the groundwater system during aquifer testing. The wells should have screened or open intervals similar to the production well so representative aquifer monitoring can be achieved during testing. If hydraulic connection between different formations is a concern, nested or multiple screened monitoring wells should be screened above or below the producing aquifer as appropriate. Construction and installation details for monitoring wells can be found in Chapter 2 of DEP's *Groundwater Monitoring Guidance Manual*.

B. Test Pump

An electrically powered submersible pump that is rated at a sufficient pumping rate should be installed in all production wells for the pumping phases of aquifer testing. The test pump capacity should not be smaller than the intended permitted capacity of the finished groundwater well. A suitable configuration that supplies electricity to the pump should be designed to insure there is no power loss and a constant discharge rate. If the power source requires the use of a hazardous fuel (gasoline, diesel, etc.) and is located within the Zone I wellhead protection area, appropriate considerations should be made. All pumps should be equipped with a check valve at the base of the pump column to prevent backflow.

VI. Observation Points

In order to allow data analysis by time-drawdown and distance-drawdown methods and to monitor for any adverse impacts on adjacent water resources, the use of appropriate observation points is necessary for aquifer tests. An observation point may be an existing well with appropriate construction that is not being pumped during the aquifer test, a well constructed for the sole purpose of collecting water-level measurements (a monitoring well), a piezometer, a stilling well, a weir or a flume. The type of observation point chosen depends on the objectives of monitoring at the site. Chapter 2 of DEP's *Groundwater Monitoring Guidance Manual* provides details on groundwater monitoring systems.

A. Observation Wells

It is recommended a minimum of three observation wells (an existing well or a monitoring well) be utilized to monitor water levels during aquifer testing. Situations involving vertical leakage, hydrogeologic boundaries or impacts to adjacent water resources may warrant the use of more. If an existing well is used, the following information should be obtained and presented in the hydrogeologic report: well owner information, function of the well, well depth, casing length, pump depth, well diameter and geology.

Observation wells should be located at increasing distances from the production well so that at least one logarithmic cycle of distance-drawdown data is provided. A typical spacing utilizing three observation wells would be approximately 100, 400 and 1,000 feet from the production well. Actual distances of the observation wells relative to the production well may be constrained by topographic limitations or land availability. Alignment will generally vary depending on the location of hydrogeologic boundaries, aquifer classification and aquifer anisotropy. The observation wells should be established in a pattern that best characterizes the suspected or known aquifer anisotropy.

B. Surface Water Monitoring Points

The effect of groundwater withdrawal on nearby streams, springs, ponds and wetlands should be monitored when the hydrogeologic setting indicates the potential for hydraulic connection between the surface water and groundwater systems. In general, monitoring points are limited to surface water features located within the estimated zone of diversion.

However, some hydrogeologic settings could trigger monitoring within the contributing area.

Surface water bodies with no outflow, such as ponds and wetlands, should be monitored via staff gauges, piezometers or monitoring wells. A piezometer may be installed adjacent to the surface water body being monitored, provided the screened interval is representative of the material underlying the surface water body. The piezometer should be constructed with a sand-packed screened interval and sealed with grout above the sand pack to prevent surface water interference.

Accurate measuring and recording instruments (weirs or flumes) should be used to measure flows in streams, springs, ponds and wetlands when the proposed groundwater withdrawal rate is 10 percent or greater than the flow of the surface water feature at the time of testing. Piezometers installed adjacent to the surface water body being monitored can be utilized to measure water levels instead of flow, especially when flow conditions are unfavorable for accurate measurement.

VII. Aquifer Testing Procedure

A successful aquifer test requires knowledge of the antecedent water-level trend, a carefully controlled constant pumping rate and accurate measurements of water levels in the production well and observation points at appropriate time intervals during background, drawdown and recovery periods. To achieve this, the aquifer test should consist of four individual components: a stepped-rate test, background test, constant-rate aquifer test and recovery test.

All aquifer test components should be scheduled to avoid heavy rain events or subsequent rapid changes in water table elevation and conducted during a period of recession when local stream flow conditions are at or below seasonal averages. Two-week advance notification should be given to DEP to allow the scheduling of a microscopic particulate analysis (MPA).

Adequate planning and design should allow for the aquifer test to be conducted on properly constructed and developed production wells and observation points according to the following procedures:

A. Monitoring and Data Documentation

It is recommended that water levels in the production well and observation points be accurately measured to the nearest 0.01 foot with digital data loggers during all components of the aquifer test. To assure all data can be correlated, data loggers should be synchronized to the same time. Manual measurements should be performed immediately prior to the start of each test component and occasionally throughout the aquifer test. An example frequency of manual measurements is every 6 hours for observation points and once each hour for the production well. Manual measurements provide backup data in the event of equipment malfunctions. Loss of data from recording system malfunctions and no backup measurements may be grounds for rejecting the results of an aquifer test. Flows should be recorded with calibrated instrumentation at appropriate frequencies during each test component.

All data generated during the aquifer test should be documented in the field. It is important that detailed notes be recorded during the aquifer test to describe the following: climatic conditions, well performance issues, equipment malfunctions, calibration records of instrumentation used and any other relevant information that could impact results of the aquifer test. A sample *Constant-Rate Pumping Test Data Form* (DEP ID: 3900-FM-BSDW0087) and *Recovery Test Data Form* (DEP ID: 3900-FM-BSDW0088) should be used to provide the raw data from the test.

B. Stepped-Rate Test

A stepped-rate test and analysis is performed to determine a sustainable pumping rate for the constant-rate aquifer test. There should be at least 3 successive equal stages of increased pumping. At each step, the pumping rate should be held constant for at least 100 minutes to assess the drawdown response. The pumping rate is increased at a constant fraction (e.g., increments of one-third for 3 steps) with the last step having a rate equal to or greater than the desired production rate. In general, the pumping rate should start at 25 percent of the blown/bailed yield or the desired yield, whichever is less, and progress to higher rates in approximately equal steps until the water level fails to equilibrate. Water levels in the production well should be measured during each individual step in accordance with the maximum frequency listed in Table 5.1. When a stepped-rate test is performed prior to the constant-rate aquifer test, water levels must be allowed to recover at least 95 percent of the original pre-pumping level. The amount of time necessary for recovery of the water level should be documented in the hydrogeologic report. The constant-rate aquifer test may not be a continuation of the last step of the stepped-rate test.

Table 5.1: Recommended Maximum Frequency of Water Level Measurements for the Stepped-Rate Test	
<i>Time Since Pumping Began</i>	<i>Time Between Measurements</i>
0-10 Minutes	1 Minute
10-20 Minutes	2 Minutes
20-60 Minutes	5 Minutes
60+ Minutes	10 Minutes

C. Background Test

A background test identifies groundwater and surface water recession trends and any background drawdown from other pumping wells. If possible, the effects from other pumping wells in the area should be controlled by having them turned off or by maintaining pumping at a constant rate. The background test should be conducted immediately prior to the constant-rate aquifer test during a period of recession. All background measurements of water levels or flows should be made at 3-hour intervals over at least a 72-hour period to establish natural trends for all zones to be monitored.

D. Constant-Rate Aquifer Test

The constant-rate aquifer test allows for the hydraulic evaluation of the aquifer. The test will also identify impacts to other water resources. The production well should be

pumped at the rate indicated by the stepped-rate test and/or the anticipated demand. Discharge should be kept within 5 percent of the constant rate at all times. The discharge rate should be checked frequently at the beginning of the test and periodically throughout the test. Discharge rates should be obtained within the first minutes of startup, and checked and recorded at no more than 5-minute intervals for the first 30 minutes of testing. After that, discharge rates should be checked and recorded at least once every 30 minutes for the duration of the test. Significant variations in pumping rates may be grounds for rejecting the results of the constant-rate aquifer test.

During the constant-rate aquifer test, water level measurements from the production well should be recorded on a logarithmic schedule. An example maximum frequency of water level measurements in the production well is listed in Table 5.2. Water levels or flows from the observation points should be recorded on a regular schedule not to exceed 10 minutes. When the site-specific hydrogeologic setting indicates the potential for rapid response in any observation point, the frequency of measurement should be adequate to capture that response. An example frequency is 1 minute between measurements.

The recommended duration of the constant-rate aquifer test for confined aquifers is a minimum of 72 hours if sufficient information is available prior to the test to demonstrate the aquifer is confined. Boundary conditions may require additional monitoring. For unconfined aquifers (such as most fractured-bedrock aquifers), the length of the constant-rate aquifer test should be a minimum of 72 hours. Testing may be extended to evaluate aquifer boundary conditions and well capabilities, as well as potential impacts to existing water supplies and the environment. All tests should be continued until drawdown has relatively stabilized.

Table 5.2: Recommended Maximum Frequency of Water Level Measurements for the Constant-Rate Aquifer Test	
<i>Time Since Pumping Began</i>	<i>Time Between Measurements</i>
0-10 Minutes	1 Minute
10-30 Minutes	5 Minutes
30-60 Minutes	10 Minutes
1-6 Hours	30 Minutes
6-24 Hours	1 Hour
24 Hours-Termination	2 Hours

E. Recovery Test

The recovery test provides additional data pertaining to aquifer hydraulics, confirmation of the constant-rate aquifer test and allows for further investigation of potential impacts on other water resources. The recovery test starts at the termination of the constant-rate aquifer test when the pump is turned off. Water level recovery in the production well and observation points should be recorded at the same frequency utilized for the constant-rate aquifer test. The recovery period should be monitored for a minimum of 24 hours or until water levels have recovered by 95 percent of the projected pre-pumping water level.

F. Discharge Water

Discharge water generated during the stepped-rate test and constant-rate aquifer test should be handled in a manner that prevents artificial recharge to the aquifer. Appropriate conveyances and/or pathways from the discharge line to an appropriate point of disposal or containment should be established. If discharge water is to be released directly to the surface, the point of discharge should be located at a minimum of 300 feet (when site conditions warrant) down dip and across strike of the production well. The discharge pipe should be equipped with a calibrated flow meter and a flow control valve. Adjustments to flow rate should be controlled by a valve in the discharge line rather than by controlling power to the pump. Proper erosion and sedimentation controls should be utilized and any necessary discharge approvals should be obtained prior to pumping. A detailed plan for the handling of discharge water should be included in the pre-drilling plan. For additional information see Appendix K of DEP's guidance document, *Erosion and Sediment Pollution Control Manual*.

G. Groundwater Sampling

At the conclusion of the constant-rate aquifer test, before the pump is turned off, groundwater samples should be collected from all production wells for chemical analysis. Laboratory analysis of groundwater samples should include all chemical constituents listed in DEP's guidance document, *New Source Sampling Requirements for Groundwater Sources for Community and Noncommunity Systems*, DEP ID: 393-3130-208 (a list is also provided in Appendix C).

Additional groundwater and surface water sampling may be necessary if the groundwater pumping is likely to have an impact on or a connection to a surface water body. The water supplier should coordinate closely with DEP on current sampling requirements, sampling plans and scheduling.

H. Water Quality Monitoring

During the constant-rate aquifer test, water quality from all production wells should be monitored. Temperature, pH, conductivity and turbidity data should be collected at 2-hour intervals and recorded in the field with a calibrated water quality instrument. Temperature and conductivity should be collected from all surface water bodies that are being monitored at the start and end of the constant-rate aquifer test. In carbonate, unconsolidated, or deeply weathered formations, continuous turbidity monitoring may be necessary. The proposed monitoring methodology should be outlined in the pre-drilling plan.

Depending on site conditions and the potential for impacts on other water resources, additional water quality monitoring may be appropriate. In this case, the water supplier coordinates with DEP regional staff in creating a monitoring plan that is representative of site conditions prior to testing.

If during any portion of the constant-rate aquifer test withdrawal water becomes turbid for an extended period of time (greater than 1 hour), displays sheen or emits odors, pumping should be stopped immediately. The constant-rate aquifer test should be

suspended if dewatering or extensive water level decline is noted in the drawdown data of any water resource being monitored. DEP should be notified immediately of all suspended tests.

I. Barometric Pressure and Precipitation Monitoring

Barometric pressure and any precipitation amounts should be recorded on-site during all phases of the aquifer test. Barometric pressure measured to the nearest 0.01 inches of mercury should be recorded at a frequency equal to water-level measurements during each test component.

Precipitation should be recorded to the nearest 0.1 inch at a minimum of 12-hour intervals. If a precipitation event occurs during any portion of the test, the duration and intensity of the event should be recorded. Any changes in these measurements should be factored into the aquifer drawdown data analysis.

VIII. Data Analysis and Hydrogeologic Report Components

A. Data Analysis and Interpretation

Various methods for the analysis of aquifer tests are available and are discussed in numerous textbooks and other publications. The selection of a method to analyze the data and subsequently interpret the results requires an understanding of the hydrogeologic system and the underlying assumptions of the analytical method. The analysis and interpretation should be conducted by a professional geologist and included in the hydrogeologic report. The analysis and interpretation of aquifer test data should include:

1. Aquifer Test Data

Include pre-test, drawdown and recovery phases for the production well and all observation points. Drawdown data should be calculated from water level measurements and reported in decimal feet. As appropriate, drawdown and recovery data should be corrected to compensate for any significant external influences (barometric pressure, precipitation, tides, etc.).

2. Plots and Graphing

Plots of step test-drawdown (semi-log), time-drawdown (log-log and semi-log), distance-drawdown (semi-log), time-recovery (semi-log) and any other relevant plots, including a copy of any type curves and match points that are used in the analysis. Log-log plots utilizing dimensionless drawdown and time ($W(u)$ and $1/u$) should also be plotted in terms of time and drawdown.

3. Aquifer Characteristics

Determination of aquifer transmissivity and storage coefficient using a method best suited for the conceptual model of the site. Evaluation of the data using several methods may be necessary. The analysis should include method selected, justification of the method and how well the assumptions implicit to that method

apply. Apparent boundary effects should also be identified and discussed. Equations used (including units) and calculations should be provided. Analysis of recovery data should not be overlooked as it can provide a check on the results obtained from the pumping data.

Determination of the hydraulic conductivity, specific capacity and estimation of the zone of influence (ZOI) (horizontal extent of the cone of depression). Various analytical methods are available to calculate the radius of influence based on certain aquifer assumptions. The Jacobs distance-drawdown method is one example.

4. Safe Yield

Determination of a safe yield for the well by considering the drawdown at observation points, available drawdown for the production well, natural recharge/discharge, any well interference effects, impacts on other water resources and the hydraulic characteristics of the aquifer system. The analysis should include the effects of 180 days of pumping with no recharge as a severe drought scenario. For complex situations involving potential impacts on other water resources, groundwater modeling should be considered.

5. Impacts from Groundwater Withdrawal

The extent of impact and how these impacts will be mitigated or remediated (i.e. long-term monitoring and sampling plans), as needed, if impacts are noted at observation points.

B. Hydrogeologic Report Components

A hydrogeologic report, signed and sealed by a professional geologist, should be submitted to DEP as part of the PWS construction permit application or as part of the *PWS Brief Inventory and Description Form* within 2 years of data collection. The report should be organized in a concise manner and contain the following information for each proposed groundwater source:

1. An electronic copy of all raw data.
2. A detailed description of the aquifer test methodology.
3. A final representative description of the geologic setting of the project area with emphasis on hydrogeologic aspects (hydrogeologic conceptual model). Supply appropriate citations for information from published literature.
4. Plot plan or detailed sketch of appropriate scale that clearly depicts the following:
 - a. All production wells and monitoring points
 - b. Pre-pumping water table contours or potentiometric surface; show natural groundwater flow direction

- c. The ZOI
 - d. The Zone I wellhead protection area
 - e. The estimated contributing area (the Zone II wellhead protection area or the Zone II and Zone III wellhead protection areas)
 - f. Sources of contamination within the ZOI and contributing area
 - g. All nearby public and private wells within the ZOI and contributing area
 - h. All nearby surface water features within the ZOI and contributing area
 - i. Geologic formations and structures (faults, folds, fracture traces, etc.) within the ZOI and contributing area
5. Stratigraphic log for each well drilled, identifying the following:
- a. Lithology, color, minerals, grain size and shape, sorting, nature of contact, fractures and other structural features, etc.
 - b. All formation changes
 - c. All water-bearing zones and associated yields
 - d. Static water level
6. As-built cross section for each well, that shows:
- a. Type, size, weight and depth of all casing(s)
 - b. Drive shoes and casing centralizers
 - c. Amount, type and depth of grout
 - d. Screened intervals/gravel pack
 - e. Static water level and date measured
 - f. Depth of production pump setting
 - g. All water-bearing zones and associated yields
7. When available, borehole camera or video imaging logs (for production wells only).
8. A copy of the completed Water Well Inventory Report.

9. Aquifer test information and data. Include:
 - a. Pre-pumping static water level
 - b. Depth of test pump setting
 - c. Starting and ending time of test cycle
 - d. Pumping rate
 - e. Stepped-rate data and graph(s)
 - f. Time-drawdown curves for production well and observation wells
 - g. Time-recovery curves for production well and observation wells
 - h. Residual drawdown vs. t/t' recovery analysis
 - i. Raw drawdown and recovery data from the production well and all observation points. Include time since pumping began (in minutes), water elevations (from below ground level), drawdown (in feet and tenths) and discharge (in gpm)
 - j. Distance-drawdown curves using data from a minimum of two observation points
 - k. Precipitation events noted on each curve
 - l. Identification and explanation of irregularities, abrupt slope changes, etc. in graphs
10. Aquifer characteristics - **show equations used and calculations.**
 - a. Hydraulic conductivity
 - b. Transmissivity
 - c. Storage coefficient
 - d. Specific capacity
11. Safe yield with justification. The well may not be permitted for a pumping rate greater than the safe yield.
12. All additional information that describes the hydraulic characteristics of the aquifer and demonstrates the suitability of the proposed source.
13. Proof of the supplier's ability to control the Zone I wellhead protection area.

14. When a spring is utilized as a source the following information should be submitted:
 - a. Results of flow and sampling studies
 - b. Topographic and geologic map of the capture area of the spring, include a description of the methodology utilized for delineation. Ginsburg and Palmer, 2002 outlines a methodology for the delineation of spring capture areas in some hydrogeologic settings
 - c. Location of all surface depressions and sinkholes within the capture area
 - d. Description of the vertical and horizontal extent of the source aquifer
 - e. Formation name
 - f. Spring type/classification (i.e., diffuse vs. conduit flow; seepage, fracture, tubular, ebbing and flowing) including justification/observations from appropriate hydrogeologic data
 - g. Physical characteristics of spring and immediate surroundings
 - h. Construction details should include the following:
 - 1) Interception and collection systems
 - 2) Diversion structures at spring discharge
 - 3) Construction materials and their placement
 - 4) Overflow piping
 - 5) Surface water diversion structures
 - 6) Cleanout drain
 - 7) Access to collection system
 - 8) Surface catchment and intake structures
15. Sample results.
 - a. New source sampling for each proposed source
 - b. MPA analysis, if applicable
 - c. Any other additional sampling, such as dye trace results, stream monitoring, Surface Water Identification Protocol (SWIP) monitoring, etc.

16. Discussion of other applicable permits or approvals which may be necessary (Include proof of resolution of PNDI conflicts).
17. A description of potential impacts that use of the new source will or could have on adjacent wetlands, surface water bodies, private or public wells, springs or other adjacent surface and subsurface water features. Discuss how the new source is hydraulically connected to the impacted feature, the anticipated extent of impact, and any proposed remediation or mitigation.

**Appendix A:
Pre-Drilling Plan**

I. Pre-Drilling Plan

A pre-drilling plan should be developed after a site survey (physical inspection) is performed by DEP staff. The plan should be prepared by the professional geologist. The well(s) should not be drilled until the plan is approved by the DEP hydrogeologist. If an existing well is being proposed as a new source of public water supply, a plan should be submitted and approved prior to aquifer testing.

The following information should be included as part of the pre-drilling plan:

A. General Information

1. The name, address and phone number of the project geologist, engineer and water supplier.
2. Purpose of the project, including water quantity needed and anticipated future quantities.
3. Anticipated water quality or quantity problems for the proposed source aquifer.
4. A detailed description of how discharge water will be handled during aquifer testing.
5. List of other agencies, appropriate river basin commissions or local municipalities which may require permits or approvals. Include records of any correspondence.
6. Resolution of Pennsylvania Natural Diversity Inventory (PNDI) conflicts, if applicable.
7. An emergency response procedure with appropriate contact information.

B. Hydrogeologic Description

1. Physiographic province of the project site.
2. Formation name(s) and lithology of target aquifer(s) and overlying formation(s).
3. Dominant permeability type(s) (e.g., fractures, bedding planes, etc.) and estimated porosity of source aquifer(s).
4. A description of expected hydrogeologic boundaries.
5. Regional strike and dip, and other relevant structural features (e.g., faults, folds, fractures, joints, etc.).
6. Geologic map showing proposed source location and regional geology.
7. Hydrogeologic cross section(s) that illustrates the conceptual groundwater flow model (see Appendix B).

8. Expected total depth of all production and observation wells.
9. Expected yield and desired yield of production well(s).

C. Project Mapping

Topographic mapping with U.S. Geological Survey (USGS) quadrangle name of appropriate scale and any other maps or plots of appropriate scale (all maps and plots should have representative scale-bar and north arrow) should clearly display the following:

1. Proposed location of the groundwater source, all wells (including existing private and public water supply wells, irrigation wells, quarries, etc.), aquifer test monitoring points and aquifer test discharge points. Latitude and longitude to an accuracy of 10 meters should be provided for all locations.
2. Estimated Zone I wellhead protection area. For additional information, see DEP's Compliance Assistance Document, *Recommended Wellhead Protection Area Zone I Delineation Method*, available from the DEP regional office.
3. Estimated outline of the area of diversion and the contributing area. Delineation methodologies are outlined in Risser and Barton, 1995; Risser and Madden, 1994; US EPA, 1987.
4. All potential hydrogeologic boundaries, recharge areas and discharge areas within the estimated contributing area. This includes all surface water bodies and potential wetlands.
5. Location and identification of all potential pollution sources (including NPDES permitted discharges) within the estimated contributing area.
6. Pre-pumping water table contours or potentiometric surface showing groundwater flow direction.
7. Fracture traces.
8. Municipal zoning (Act 247) and sewage facilities planning (Act 537) area of diversion and the contributing area. (Indicate zoning and the planned method of sewage disposal.)

D. Preliminary Monitoring Plan

A site specific monitoring plan in accordance with the hydrogeologic description and project mapping should be included as part of the pre-drilling plan. To adequately characterize the proposed source aquifer the monitoring plan may need to be refined after well drilling. Include the following:

1. A detailed description that clearly defines the monitoring network to be utilized during the aquifer test. Monitor as many onsite and offsite water resources as necessary to accurately describe the relationship between the well, aquifer and any surface water bodies. The monitoring plan should also include a description of water quality monitoring in the production well and any monitoring points.
2. A description of methods to identify and assess potential impacts that construction and use of a new source(s) will, or could have, on adjacent wetlands, surface water bodies, public and private wells, springs, or other surface and subsurface water features.

E. Well Construction

Proposed well construction specifications should be provided for all production and observation wells. Include the following:

1. Description of drilling method(s).
2. Casing.
 - a. Size of annular opening
 - b. Type, diameter, weight and depth of all casing
 - c. Use of drive shoes and casing centralizers
 - d. Type of joint
3. Grout.
 - a. Type
 - b. Estimated quantity
 - c. Method of placement
 - d. Emergency procedures - lost circulation procedures, etc.
4. Well Screen.
 - a. Screen material (e.g., polyvinyl chloride, ferrous, etc.)

- b. Anticipated screened interval
 - c. Screen design
5. Well completion.
 - a. Type of production pump and anticipated pump depth
 - b. Plumbness and alignment test
 - c. Pitless unit or adapter installation
 6. Proposed well development procedures.
 7. Well logging procedure. (Drill cuttings should be collected at a maximum of 5-foot intervals and at all pronounced changes in lithology/formation.).
 8. Procedure for disposing of cuttings and drilling fluids ensuring that proper erosion and sedimentation controls are used including a detailed plan on how discharge water will be handled.
 9. All unused boreholes should be properly abandoned. *Note: A certificate of abandonment, issued by the Pennsylvania Topographic and Geologic Survey for all abandoned wells should be included in the permit application in the event that any wells/boreholes are abandoned. Abandonment guidelines can be found in Chapter 7 of DEP's Groundwater Monitoring Manual.*

F. Sampling and Analytical Description

1. Clearly indicate the existence of a hose bibb sampling port.
2. Determine if the requirements of DEP's Surface Water Identification Protocol (SWIP) are appropriate. For details on this procedure see DEP's guidance, *Summary for Key Requirements of Surface Water Identification Protocol*, DEP ID: 383-0810-206. If SWIP monitoring does not apply to the proposed groundwater source provide supporting information.

II. Pre-Drilling Plan Modifications

An addendum to the pre-drilling plan that summarizes any modifications that may result from well drilling should be prepared by the professional geologist and submitted to DEP. Aquifer testing should not commence until the addendum is approved by the DEP hydrogeologist. Common modifications to the pre-drilling plan are outlined below:

A. Hydrogeologic Modifications

Some common modifications regarding the site hydrogeology that may result from well drilling activities can include (but are not limited to) the following:

1. Lithology of target aquifer(s) and overlying formation(s).
2. Dominant permeability type(s) (e.g., fractures, bedding planes, etc.) and estimated porosity of source aquifer(s).
3. Hydrogeologic boundaries.
4. The conceptual groundwater flow model (hydrogeologic setting).
5. Expected total depth of all production and observation wells.
6. Expected yield and desired yield of production well(s).
7. The estimated Zone I wellhead protection area, the area of diversion and the contributing area.
8. Pre-pumping water table contours or potentiometric surface showing groundwater flow direction.

B. Geologic and Well Construction Logs

Finalized geologic and well construction logs should be provided for all observation wells and production wells. The production wells should be constructed to the community system design standards outlined in Part II of DEP's *Public Water Supply Manual*.

C. Final Monitoring Network

A finalized monitoring network should clearly display all monitoring points, the production well(s) and the aquifer test discharge point(s) in map view. These locations should have associated locational data to an accuracy of 10 meters. The monitoring points should be clearly designated as a groundwater or surface water monitoring point. Additionally, all groundwater monitoring points should be clearly labeled as drilled or existing wells. When appropriate, provide proof of access to all private monitoring points.

D. Discharge Water

A finalized plan should clearly outline a procedure for handling discharge water generated from groundwater pumping. Approvals from DEP or other agencies should also be demonstrated.

E. Monitoring Equipment and Data Collection Procedures

A description of all monitoring equipment and associated data collection procedures should be provided.

F. Aquifer Testing Schedule

An aquifer testing schedule should clearly outline the anticipated starting and ending dates/times of all aquifer testing components (the stepped rate test, background monitoring, the constant-rate aquifer test and recovery monitoring). Coordination with DEP on dates and times of all testing activities is essential for a groundwater withdrawal project.

**Appendix B:
Conceptual Model Questionnaire**

CONCEPTUAL MODEL QUESTIONNAIRE (modified from Reese et al., 2004)	
Setting — Use available literature and any site-specific data	
Location	Physiographic province, section and specific area.
Topography	What is the topography in relationship to the well site? Look at specific topographic types such as mountain slopes or valley floors. How does the topography affect surface and groundwater flow? What are the geological factors controlling the topography?
Surface water flow and groundwater flow	Are groundwater and surface water boundaries the same? What is the nature of interaction between surface water features and groundwater? Does groundwater discharge to adjacent streams or other surface water features without a significant regional component? Is there any reason to believe that groundwater flows opposite to topography. Stream patterns, presence of losing streams, swallow holes, blind valleys, wetlands, springs, recharge and discharge areas, geologic barriers, etc. are important considerations. A water-level map displays groundwater flow directions.
General geology	What are the major formations, aquifers, and structural and stratigraphic features of the site? What is the depth to bedrock? Are there outcrops in the area?
Hydrogeologic framework and boundary conditions — Use available literature and any site-specific data	
Hydrogeologic boundaries	Does the geology of the area indicate lithologic or structural boundaries that could control or alter groundwater flow? Groundwater and surface basin boundaries, formation contacts, and extent and variability of aquifers should be assessed. What is the overburden thickness? Is geologic structure related to groundwater basin divides?
Geologic structural controls; man-made controls, stresses	What is the regional strike of bedrock? Is there much local variation? Are there igneous intrusions present? Folds/faults? If carbonate rocks are present, are there adjacent non-carbonate rocks that affect the aquifer system? Note regional structure - strike and dip, geologic barriers to groundwater flow; recharge boundaries/divides; fracture patterns (orientation); shale horizons; evidence and degree of carbonate rock karstification (diffuse vs. conduit flow); location of streams and rivers (are surface water divides transcended?). Note features and properties such as fracture traces, lineaments, joint spacing; karst features such as aligned sinkholes and closed depressions; diabase dikes or sills, buried valleys, local glacial features (kames, eskers, glacial lakes sediments, etc.), alluvium, colluvium, etc. Are there adjacent pumping wells, mines or quarries, or geologic factors that may affect groundwater flow? How is the groundwater being used? Are there sources of recharge such as septic systems that could contribute to groundwater?
Aquifer conditions	Is the target aquifer unconfined, semi-confined or confined? What are the known confining units? What is the extent of fracturing in the bedrock; depth of overburden. Are there karst features present? Are there perched water zones?

Aquifer properties — Use available literature and any site-specific data	
Anisotropy	What is the suspected anisotropy and associated k-min/k-max ratios? Anisotropy can be estimated from structural data such as bedding and fracture traces displayed on steronets and rose diagrams. Fracture traces and orientation of stream segments can help in identifying anisotropy. Fracture and joint trend directions along with bedrock strike can provide clues to any preferential flow paths. Groundwater flow in gently dipping and folded settings often moves at contacts of formations with significantly different hydraulic properties.
Groundwater flow	What are the expected or mapped water table configuration and flow directions? Where are the recharge and discharge areas? Recharge areas of a watershed typically cover 60 to over 90 percent of the area. Discharge zones are typically located at topographic lows, breaks in slope, or in deep valleys with adjacent “impermeable” boundaries. Geological settings like tilted rocks can influence the location of recharge and discharge. Are there adjacent pumping wells, mines or quarries, or geologic factors that may affect groundwater flow? Note presence and locations of springs and wetlands. Is perched groundwater present? Is there a deep component of groundwater flow? What are the known or potential confining units? For carbonate aquifers, consider conduit vs. diffused groundwater flow. Are there impacts from mining operations such as rock quarries or coal mines? Note the shape of the groundwater basin and potential flow paths. Are there areas of high transmissivity (for example, buried valleys or carbonate valleys) that serve as the main thoroughfare for groundwater flow? Is there information available on the age of groundwater?
Depth to water	What is the depth to water table? (generally not perched zones); How does the geology affect the depth to water? How variable is the depth to water?
Geochemistry	What is the general water quality, geochemistry, and geochemical patterns at springs and wells. What is the range of geochemistry? How does groundwater flow path affect geochemistry?
Hydraulic conductivity	Consider the ranges and medians of hydraulic conductivity by geologic unit. Consider vertical vs. horizontal values and anisotropic effects.
Storage coefficient	What are the values for confined aquifers (by geologic unit)?
Specific yield	What are the values for unconfined aquifers (by geologic unit)?
Recharge	Recharge is measured in inches per year or gallons per day per square mile. One million gallons per day per square mile equals 21 inches of recharge per year; one inch of precipitation per year equals 47,610 gpd/mi ² . If there is no change in groundwater storage, the stream baseflow from groundwater will typically equal the recharge of the watershed. Recharge is controlled by climate, vegetation, and soil characteristics. Thus, changes in recharge occur seasonally and from year to year. Consider also the effects of varying or changing land uses on recharge values, and the potential effects of discharge from septic systems or leaking storm drains. Areas underlain by deep mining (especially longwall mining) should also be considered for possible changes to the groundwater system. Consider delineating discharge areas (which may change based on changing seasonal climate conditions and other groundwater withdrawals).
Porosity	Porosity is reported as a percent of the consolidated or unconsolidated aquifer.
Transmissivity	What is the range or median of transmissivity by geologic unit? Convert from hydraulic conductivity using aquifer thickness, or develop approximation of transmissivity using specific capacity value.

**Appendix C:
New Source Sampling Laboratory Analysis Tables**

VOLATILE ORGANIC CHEMICALS (VOCs):

BENZENE	trans-1,2-DICHLOROETHYLENE	TOLUENE
CARBON TETRACHLORIDE	DICHLOROMETHANE	1,2,4-TRICHLOROBENZENE
o-DICHLOROBENZENE	1,2-DICHLOROPROPANE	1,1,1-TRICHLOROETHANE
para-DICHLOROBENZENE	ETHYLBENZENE	1,1,2-TRICHLOROETHANE
1,2-DICHLOROETHANE	MONOCHLOROBENZENE	TRICHLOROETHYLENE
1,1-DICHLOROETHYLENE	STYRENE	VINYL CHLORIDE (See NOTE)
cis-1,2-DICHLOROETHYLENE	TETRACHLOROETHYLENE	XYLENES (Total)

NOTE: Monitoring for vinyl chloride is only required when one or more of the following two-carbon compounds are detected: trichloroethylene, tetrachloroethylene, trans-1,2-dichloroethylene, cis-1,2-dichloroethylene, 1,2-dichloroethane, 1,1-dichloroethylene, 1,1,1-trichloroethane.

SYNTHETIC ORGANIC CHEMICALS (SOCs):

ALACHLOR	DIQUAT	METHOXYCHLOR
ATRAZINE	ENDOTHALL	OXAMYL (VYDATE)
BENZO(A)PYRENE	ETHYLENE DIBROMIDE (EDB)	PCBs ¹
CARBOFURAN	ENDRIN	PENTACHLOROPHENOL
CHLORDANE	GLYPHOSATE	PICLORAM
DALAPON	HEPTACHLOR	SIMAZINE
DI(2-ETHYLHEXYL) ADIPATE	HEPTACHLOR EPOXIDE	TOXAPHENE
DI(2-ETHYLHEXYL) PHTHALATE	HEXACHLOROBENZENE	2, 3, 7, 8-TCDD (DIOXIN) ¹
DIBROMOCHLOROPROPANE (DBCP)	HEXACHLOROCYCLOPENTADIENE	2, 4-D
DINOSEB	LINDANE	2, 4, 5-TP (SILVEX)

1. Monitoring for PCBs and/or dioxin is required when there is a contamination source within 1,000 feet of the new groundwater source. Provide details of the assessment in Public Water Supply Module 3A, Part U to support a finding of no sources of contamination.

INORGANIC CHEMICALS (IOCs):

ANTIMONY	CHROMIUM	NICKEL
ARSENIC	COPPER	NITRATE (as Nitrogen)
ASBESTOS (see NOTE)	CYANIDE (as free cyanide)	NITRITE (as Nitrogen)
BARIUM	FLUORIDE	SELENIUM
BERYLLIUM	LEAD	THALLIUM
CADMIUM	MERCURY	

NOTE: Monitoring for asbestos is required when DEP has reason to believe the source is vulnerable to contamination.

RADIONUCLIDES:

GROSS ALPHA	GROSS BETA (See NOTE)
RADIUM-226, RADIUM-228	URANIUM

NOTE: If the Gross Beta exceeds 50 pCi/L, analyze the same or equivalent sample to identify the major radioactive constituents present.

MICROBIOLOGICAL CONTAMINANTS:

TOTAL COLIFORMS CONCENTRATION	Three (3) separate samples obtained at 15-minute intervals immediately prior to the conclusion of the constant-rate aquifer test. For each Total Coliform positive sample, analyze the same or equivalent sample for <i>E. coli</i> concentration.
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SECONDARY CONTAMINANTS AND OTHERS:		
ALKALINITY ALUMINUM CHLORIDE COLOR FOAMING AGENTS	HARDNESS IRON MANGANESE pH (See NOTE) SILVER	SULFATE TEMPERATURE (See NOTE) TOTAL DISSOLVED SOLIDS TOTAL ORGANIC CARBON TURBIDITY (NTU) ZINC
NOTE: Temperature and pH measurements may be obtained in the field within 15 minutes of sample collection.		
MICROSCOPIC PARTICULATE ANALYSIS (MPA)	The project applicant should coordinate with appropriate DEP regional staff regarding MPA sampling. Sampling should be conducted by DEP or the project applicant for new groundwater sources which fall within the criteria of the <i>Guidance for Surface Water Identification Protocol</i> , DEP ID: 383-3500-106, available on DEP's website at www.dep.state.pa.us .	

References Cited

- Brown, R. H., 1963, The cone of depression and the area of diversion around a well in an infinite strip aquifer subject to uniform recharge: U.S. Geological Survey Water-Supply Paper 1545C, p. C69-C85.
- Ginsburg, M., and Palmer, A., 2002, Delineation of source-water protection areas in karst aquifers in the Ridge and Valley and Appalachian Plateaus physiographic provinces: rules of thumb for estimating the capture zones of springs and wells: Washington, DC, United States Environmental Protection Agency, EPA Document 816-R-02-0145.
- Morrissey, D. J., 1987, Estimation of the recharge area contributing water to a pumped well in a glacial drift, river-valley aquifer, U.S. Geological Survey Open-File Report 86-543.
- Reese, S., Lee, J., and Diehl, J., 2004 (unpublished material), draft Framework for developing a conceptual groundwater flow models in Pennsylvania, Pennsylvania Department of Environmental Protection and Pennsylvania Department of Conservation and Natural Resources.
- Risser, D. W., and Barton, G. J., 1995, A strategy for delineating the area of ground-water contribution to wells completed in fractured bedrock aquifers in Pennsylvania, U.S. Geological Survey Water-Resources Investigations Report 95-4033.
- Risser, D. W., and Madden, Jr., T. M., 1994, Evaluation of methods for delineating areas that contribute water to wells completed in valley-fill aquifers in Pennsylvania, U.S. Geological Survey Open-File Report 92-635.
- U.S. Environmental Protection Agency, 1987, Guidelines for delineation of wellhead protection areas, EPA 440/6-87-010.

Notes:

- 1) All DEP publications referenced in this document can be obtained from the DEP eLibrary website: www.elibrary.dep.state.pa.us/dsweb
- 2) All DEP regulations referenced in this document can be obtained from the following website: www.pacode.com/secure/data/025/025toc.html