# Appendix A

## Groundwater Monitoring Guidance

# TABLE OF CONTENTS

# APPENDIX A:  GROUNDWATER MONITORING GUIDANCE

When groundwater is an affected medium, monitoring it is an extremely important part of site characterization, fate and transport assessment, and ultimately, demonstrating attainment of a cleanup standard at Act 2 sites.  Taking this under consideration, the Groundwater Monitoring Guidance identifies technical considerations for performing detailed yet concise hydrogeologic investigations and groundwater monitoring programs at Act 2 sites.  The purpose of this guidance is to ensure consistency within the Department and to inform the regulated community of DEP's technical recommendations and the basis for them.

The methods and practices described in this guidance are not intended to be the only methods and practices available to a remediator for attaining compliance with Act 2 regulations.  The procedures used to meet requirements should be tailored to the specific needs of the individual site and Act 2 project and based on the history, logistics, and unique circumstances of those sites.  The guidance is not intended to be a rigid step-by-step approach that is utilized in all situations.  The Department recommends that site remediators consult with DEP Regional Office staff for assistance in evaluating and understanding site characterization information for a more efficient Act 2 cleanup.

## A. Overview

### 1. Introduction

Monitoring of groundwater quality is an important component in the application of and compliance with Act 2 of 1995, the Land Recycling and Environmental Remediation Standards Act (Act 2, 35 P.S. §§ 6026.101-2026.908).  The goal for monitoring groundwater quality is to obtain reliable data and information that is representative of aquifer characteristics, groundwater flow direction, and physical and chemical characteristics of the groundwater.

Before beginning a hydrogeologic investigation at an Act 2 site, a conceptual site model (CSM) should be developed based on site geology and hydrogeology and the characteristics of the release.  The CSM should estimate distribution of predominant geologic units, flow conditions, location of aquifers and aquitards (if known), water table surface and other pertinent hydrogeologic factors present at the site.  Coupled with hydrogeologic properties at the Act 2 site, the CSM should consider the type of contaminant which has been released and its physical properties (e.g., petroleum-based or solvent-based, weathered vs. fresh, etc.), the manner of release to the environment, and the volume of the release as can best be determined.

Typical groundwater quality monitoring at Act 2 sites may include:

- Background monitoring:  relating to determination of background conditions in accordance with the Act 2 background cleanup standard (e.g. establishing if a groundwater contaminant is naturally occurring, an areawide problem typically resulting from historic, areawide releases, or from an upgradient source).  The results of background groundwater monitoring will form a basis against which future monitoring results will be compared to established background values for specific regulated substances of concern, develop groundwater quality trend analyses, or remediation effectiveness under Act 2 when the background cleanup standard is selected.

- Site Characterization: During site characterization, groundwater monitoring wells may be installed and sampled at an Act 2 site throughout the area(s) of contamination, as well as in areas not affected by the release of any regulated substance. Some of the data collected at the monitoring well locations may include groundwater elevations, which are then used to calculate groundwater flow direction and hydraulic gradient, permeability of aquifer materials, porosity of the aquifer, the types of regulated substances present and their concentrations, and the spatial variation in concentration, both horizontally and vertically. A fate and transport assessment most likely should be implemented during this phase of the Act 2 investigation.

- Attainment monitoring: Attainment monitoring of groundwater is performed to demonstrate that the selected Act 2 cleanup standard has been attained at the Point of Compliance (POC). Refer to Section II.B of this guidance for additional information on this concept. Attainment monitoring is also utilized to determine the effectiveness of groundwater cleanup activities.

- Postremedial monitoring: Postclosure monitoring is conducted to determine any changes in groundwater quality after the cessation of a regulated activity or activities. This monitoring may also be part of a postremedial care plan, such as periodic monitoring of sentinel wells. Analytes most likely to be included are those which were monitored during site characterization and/or attainment monitoring.

## 2. References

Alaska Department of Environmental Conservation, September 2013, Division of Spill Prevention and Response Contamination Sites Program, Monitoring Well Guidance.

## B. Monitoring Well Types and Construction

### 1. Objectives of Monitoring Wells

Monitoring wells should be located and constructed to provide the controlled access necessary to characterize the groundwater at an Act 2 site. Wells should be constructed by a driller who is licensed by the Commonwealth of Pennsylvania (Act 610 of 1956, 32 P.S. § 645.12, and 17 Pa. Code Chapter 47). Drillers do not need to be licensed to install piezometers, temporary well points, or in-situ sampling probes.

Monitoring wells should effectively achieve one or more of the following objectives:

- Provide access to the groundwater system for collection of water samples.
- Measure the hydraulic head at a specific location in the groundwater flow system.
- Provide access for conducting tests or collecting information necessary to characterize the chemical properties of aquifer materials or their hydrologic properties.

While achieving these objectives, the groundwater monitoring system should also preserve the conditions of the subsurface that is penetrated, but not monitored. For example, a well designed to monitor a bedrock aquifer should be designed and installed with minimal or no impact to the flow system in the unconsolidated material overlying the bedrock.

Although monitoring (or observation) wells may be used to measure water levels and then determine the configuration of the water table, or other potentiometric surface, the focus of this appendix is groundwater quality monitoring. Specifically, this appendix provides guidance for the monitoring of groundwater at Act 2 sites.

### 2. Types of Groundwater Monitoring Systems

Groundwater monitoring systems range from the simple to the complex. Each system has its own value and use in the monitoring environment. Various types of groundwater monitoring systems are described below. General recommendations for the construction of single-screened wells and open boreholes are shown in Figures A-1 and A-2. Site-specific circumstances may require modifications to the recommended construction details.

<u>Open boreholes</u> - These boreholes are typically drilled into competent bedrock with the casing extending completely through the overburden (unconsolidated material) and into the competent rock below. Note that a vertical conduit is created which may intercept active groundwater flow zones (controlled by primary porosity and secondary porosity; i.e. fractures, bedding planes, solution cavities) previously not in contact with each other, potentially resulting in cross contamination. Recommended installation details are shown in Figure A-1.

**Figure A-1: Recommended Construction of an Open Borehole Well**

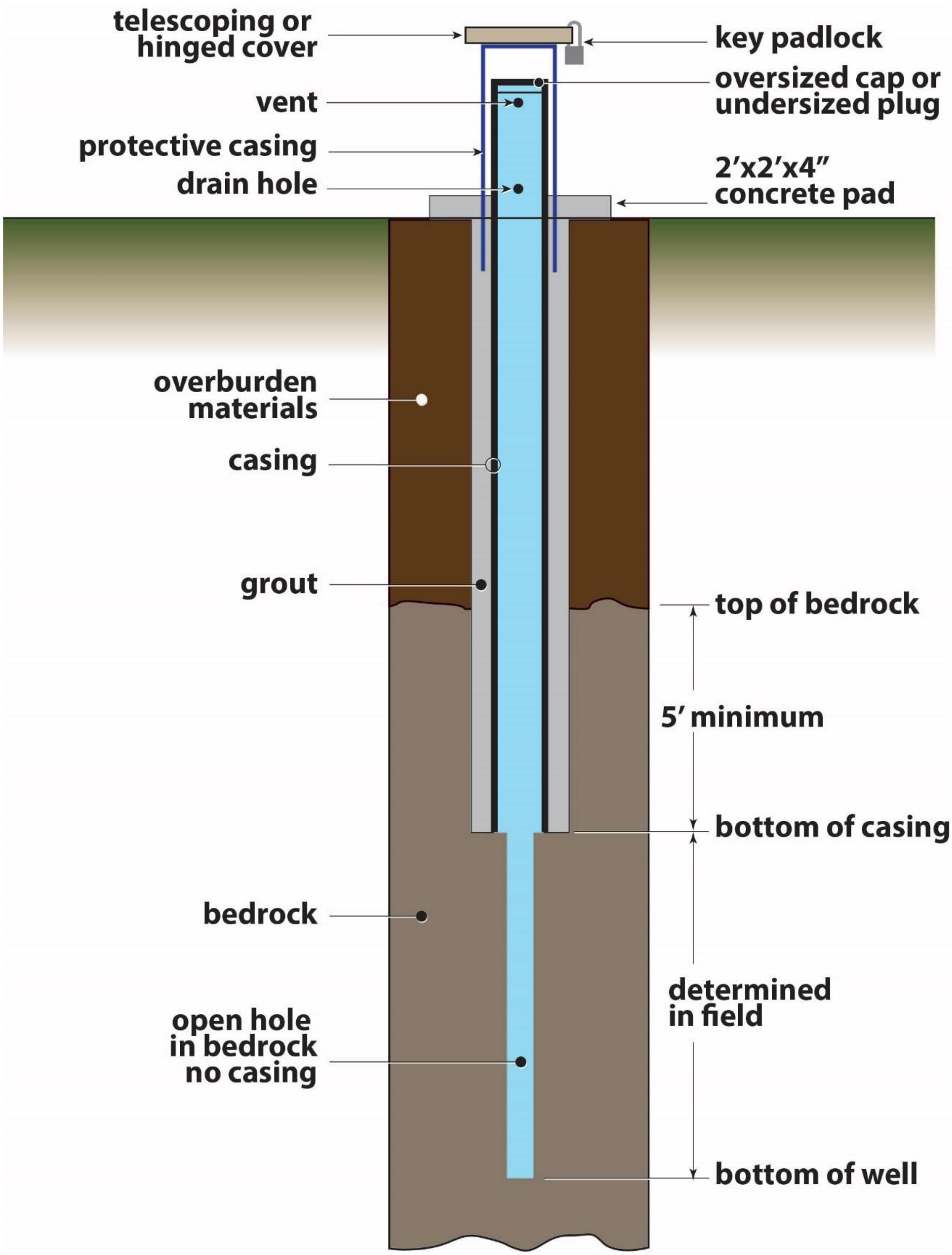


**Figure A-2: Recommended Construction of a Single-Screened Well**

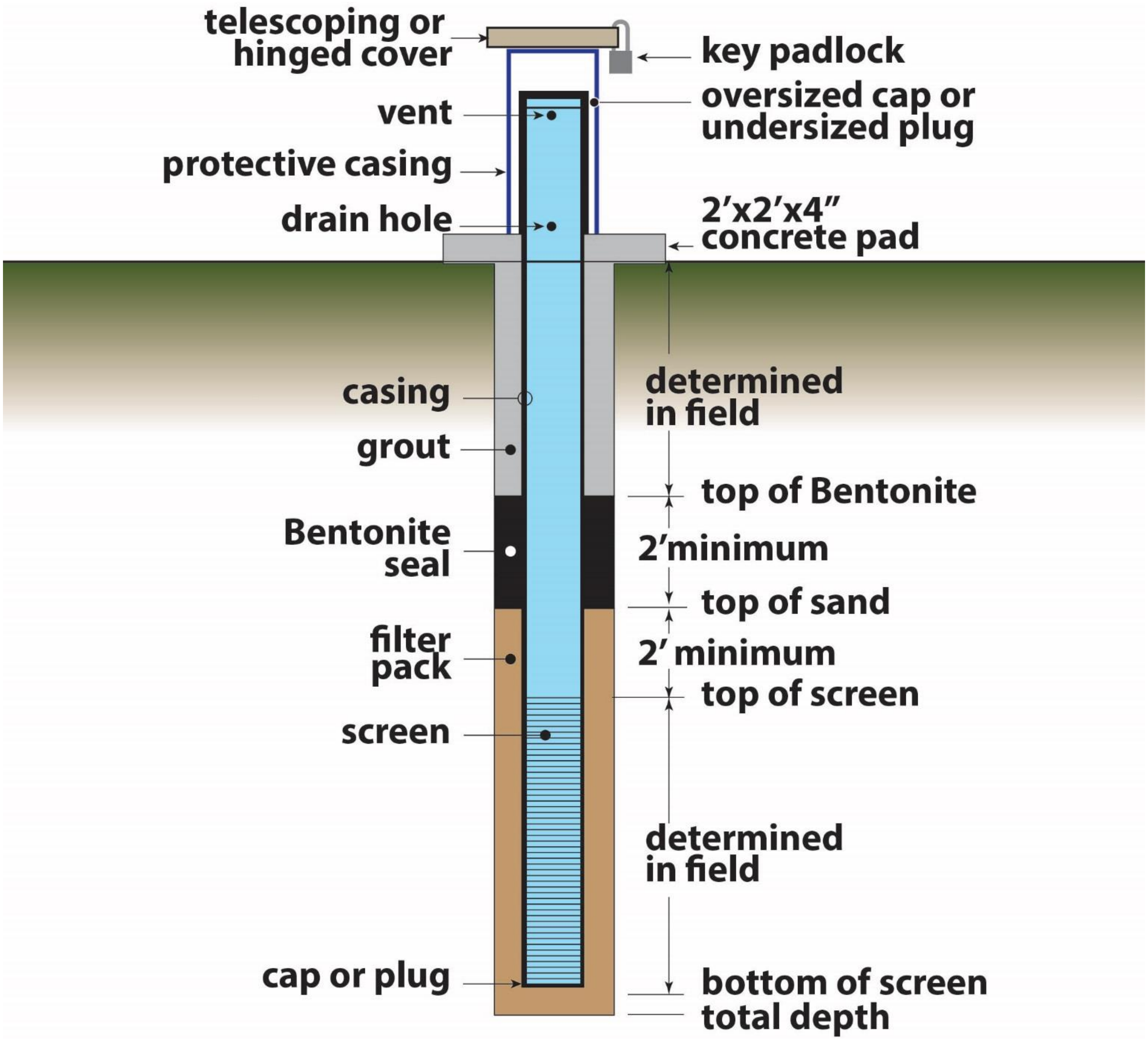
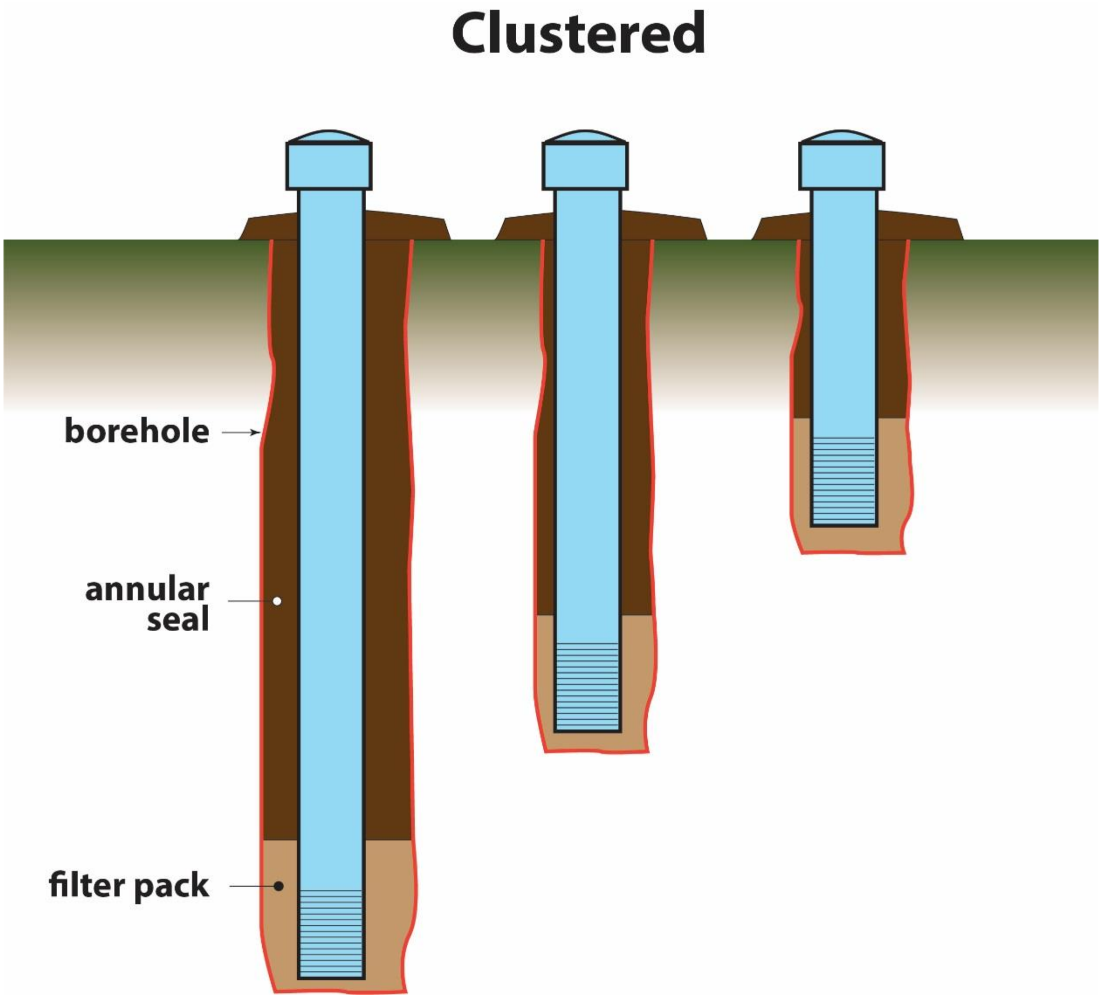


**Figure A-3: Example of a Well Cluster**




Single screened wells - These wells consist of a prefabricated screen of polyvinylchloride plastic, stainless steel, etc., that is inserted into an open borehole. Clean sand or gravel is placed around the annular space of the screen for the entire vertical distance of the screen length and slightly higher past the connecting screen and well casing. Recommended installation details are shown in Figure A-2.

Well clusters - Well clusters, or a well nest, consist of the construction of open boreholes or screened monitoring wells in a specific location, with each well monitoring a different depth or zone of groundwater. An example of a well cluster is shown in Figure A-3.

Well points - Well points are usually short lengths (i.e., 1-3 feet) of screen attached to a hardened metal point so that the entire unit can be driven, pushed, or drilled to the desired depth for monitoring. (This method is usually limited to shallow, unconsolidated formations.)

Piezometers - These are small diameter wells, generally non-pumping, with a very short well screen or section of slotted pipe at the end that is used to measure the hydraulic head at a certain point below the water table or other potentiometric surface.

## 3. Choice of Monitoring System

The type of monitoring system chosen depends on the objectives of monitoring at the site. Once the target zones, or areal locations and depths that are the most likely to be impacted by the release are defined, monitoring is often adequately accomplished by using open rock boreholes or single-screened wells that monitor the entire saturated thickness, or a large portion of the target zone.

Where contamination has been detected and definition of vertical contaminant stratification is desired, wells that monitor more discrete intervals of the target zone, or individual aquifers, usually need to be constructed. In this case, well clusters such as shown in Figure A-3 will often be the construction design of choice, although open holes that monitor a short vertical interval or single water-bearing zone also may have application. As the flow beneath the site is better understood, the monitoring system typically will target more specific depths and locations.

Well points, or in-situ sampling probes (direct push technology), can be valuable reconnaissance tools for preliminary site characterizations, or for determining the locations of permanent monitoring wells (see EPA, 1993 and ITRC, 2006). However, in-situ sampling probes can miss a light nonaqueous phase liquid (LNAPL) on the water table and may have problems penetrating coarse sands and gravel (where contamination may be located). Other potential problems include very slow fill times in clayey sediments and significant capture of fines in the sample.

Special well construction will be needed to monitor for certain types of contaminants. **For example, if an LNAPL is a concern, the well screen should be open, bridging the top of the water table and within the zone of fluctuation, so that the LNAPL contaminants will not be cased-off.**

## 4. Minimum Construction Standards

To properly meet the objectives listed in Section B.1, monitoring wells should be designed and constructed using minimum standards in each of the following categories.

1) Materials

2) Assembly and installation

3) Well development

4) Recordkeeping and reporting

**Figure A-4: Examples of Target Zones**

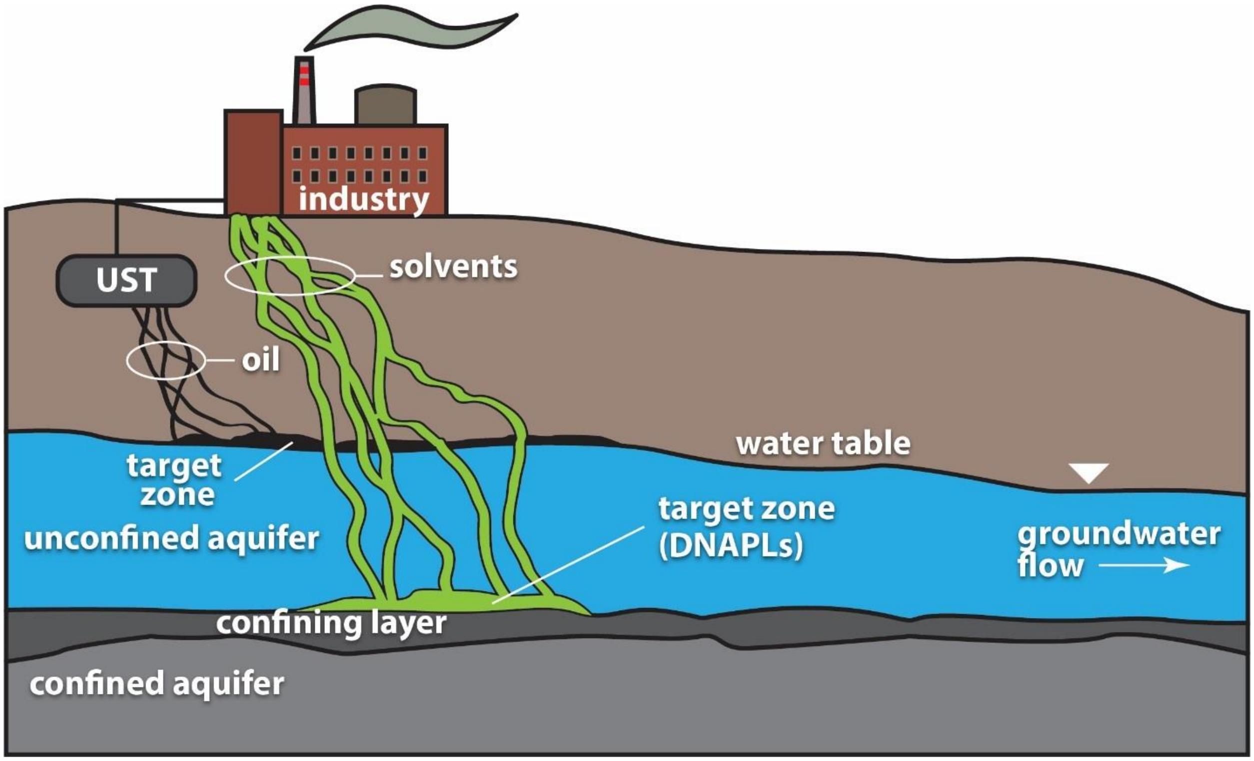
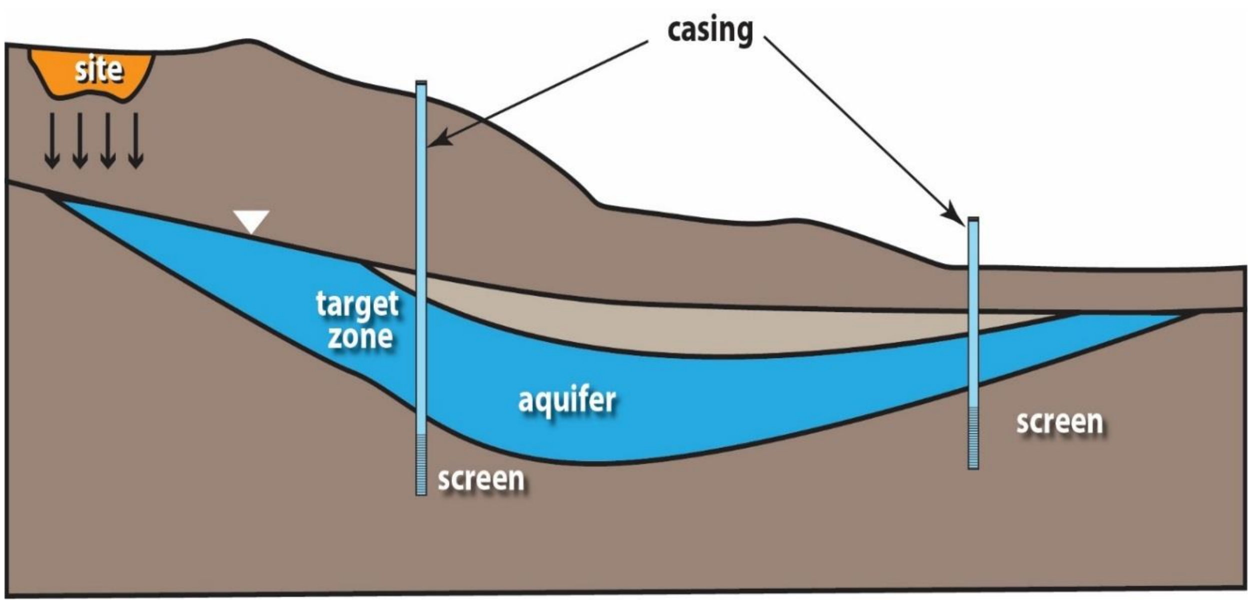



**Figure A-5: Monitoring Well Screens Placed Too Deeply Below the Target Zone to Detect Contamination**



Different standards and practices may be necessary depending upon the monitoring objectives of an individual site. Monitoring wells constructed to meet multiple objectives should employ the standards of the most rigorous objective. For instance, a well point may be suitable for monitoring hydraulic head, but may not be optimum for collecting samples. Therefore, a well proposed to monitor head and collect water samples should be designed as a conventional, screened well and not as a well point. In addition, construction methods, materials, and well development of each point in the plan must not compromise the objective of other monitoring wells in the well system.

**a) Materials**

Materials that are used in construction of a monitoring well should not contaminate the groundwater being monitored. A list of materials should include, but not be limited to, the drilling tools and equipment, casing, riser pipe, well screen, centralizers (if needed), annular sealant, filter pack, and drilling fluids or additives. All materials should be of adequate size and of competent strength to meet the objectives of the monitoring point. All materials introduced into the boring should be free of chemicals or other contaminants that could compromise the monitoring well or other downgradient wells. Practices must be employed to minimize the potential for contamination of the materials during storage, assembly, and installation. Specific cleaning procedures should be employed in situations where the materials might introduce contaminants to the groundwater system. Well screens and risers should be coupled using either water-tight flush-joint threads or thermal welds. Solvent welded couplings are not recommended for monitoring well construction.

**b) Assembly and Installation**

Equipment and techniques should be used that create a stable, open, vertical borehole of large enough diameter to ensure that the monitoring well can be installed as designed, while minimizing the impact on the zone(s) being monitored. When drill cuttings and groundwater removed during construction will likely be contaminated, procedures commensurate with the type and level of contamination should be followed for the handling, storage, and disposal of the contaminated material. Whenever feasible, drilling procedures that do not introduce water or other liquids into the borehole should be utilized. When the use of drilling fluids is unavoidable, the fluid should have as little impact on the constituents of interest as possible. If air or other gas is used as the drilling fluid, the compressor should be equipped with an oil air filter or an oil trap.

The well screen and riser assembly should be installed using procedures that ensure the integrity of the assembly. If water or other ballast is used, it should be of known and compatible chemistry with the water in the boring. Unless designed otherwise, the assembly should be installed plumb and in the center of the boring. Centralizers of proper spacing and diameter can be used. Depending upon the physical environment, the well should be finished as a secure stick-up or flushmount at the discretion of the project geologist. Either completed type of well should be securely capped to prevent the entry of foreign material.

Installation of the filter pack, sealants, or other materials in the annular space should be done using tremie pipes or other accepted practices. Protective casing and locking well caps must be installed, and any other necessary measures must be taken to ensure that the monitoring well is protected from vandalism and accidental damage. To reduce misidentification, all monitoring wells constructed in developed areas, or in any location where they may be mistaken for other structures (such as tank-fill tubes, drains, and breather tubes), should have a locking cap conspicuously labeled "Monitoring Well" (preferably by the well-cap manufacturer). In addition, locks for the monitoring wells should use a key pattern different from locks on other structures at the site. It is also advisable that the well identification number be placed on both the inside and outside of the protective casing.

**c) Well Development**

After installation, groundwater monitoring wells should be developed to:

- Correct damage to the geological formation caused by the drilling process;
- Restore the natural water quality of the aquifer in and around the well;
- Optimize hydraulic communication between the geologic formation and the well screen; and
- Create an effective filter pack around the well screen.

Well development is necessary to provide groundwater samples that represent natural undisturbed hydrogeological conditions. When properly developed, a monitoring well will produce samples of acceptably low turbidity (less than 10 Nephelometric Turbidity Units (NTUs) as recommended by U.S. EPA, 2013). Low turbidity is desirable as turbidity may interfere with subsequent analyses, especially for constituents that sorb to fine-grained materials, such as metals (CEPA, 2014). Well development stresses the formation and filter pack so that fine-grained materials are mobilized, pulled through the well screen into the well, and removed by pumping.

Well development should continue until as much of the fine-grained materials present in the well column have been removed as possible. It is important to record pumping rates utilized during well development. Purging and sampling rates should not exceed the maximum pumping rate used during well development. When it is likely that the water removed during development will be contaminated, procedures commensurate with the type and level of contamination should be utilized and documented for the handling, storage, and disposal of the contaminated material. Development methods should minimize the introduction of materials that might compromise the objective of the monitoring. If air is used, the compressor should have an oil air filter or oil trap.

Repeated well development may be conducted as necessary at the discretion of the project geologist, especially if clogged screens or biofouling are evident.

**d) Recordkeeping and Reporting**

Because interpretation of monitoring data from a monitoring well is spatially dependent on both the activity being monitored and other monitoring wells in the system, records and samples of the materials used to construct and drill the monitoring well should be kept. Following construction, accurate horizontal and vertical surveys should be performed. The surveys should be completed by personnel knowledgeable in land surveying techniques. A permanent reference point should be made by notching the riser pipe. Whenever possible, all reference points should be established in relation to an established National Geodetic Vertical Datum (NGVD). Monitoring well locations should be surveyed to ±1 linear foot, and monitoring well elevations should be to the nearest .01 foot. Elevations of the protective casing (with the cap off or hinged back), the well casing, and the ground surface should be surveyed for each monitoring well (see Nielsen, 1991). DEP-permitted facilities are generally required to record the latitude and longitude for each monitoring well (this also is recommended for non-permitted facilities).

A groundwater monitoring network report should be prepared. This report should include copies of the well boring logs, test pit and exploratory borehole logs; details on the construction of each monitoring point; maps, air photos or other information necessary to fully describe the location and spatial relationship of the points in the monitoring system; and a recommended decommissioning procedure consistent with the applicable regulatory program and the well decommissioning procedures recommended in Section E of this appendix.

Monitoring well logs should be prepared and should describe, at a minimum, the date of construction; the thickness and composition of the geologic units (identification of stratigraphic units should be completed on the well log using the Unified Soil Classification System); the location and type of samples collected; the nature of fractures and other discontinuities encountered; the nature and occurrence of groundwater encountered during construction, including the depth and yield of water-bearing zones; headspace of photoionization detector (PID) readings collected; any observations of contamination (e.g. NAPL); and the static water level upon completing construction.

A well completion plan should also be included in the monitoring network report. Each plan should include information on the length, location, slot size, and nature of filter pack for each screen; type, location and quantity of material used as annular seals and filler; description of the type and effectiveness of well development employed; and notes describing how the well, as constructed, differs from its original design and/or location.

The reports described above do not relieve the driller from the obligation to submit, for each well drilled, a Water Well Completion Report to the Department of Conservation and Natural Resources (DCNR), Bureau of Topographic and Geologic Survey, as required by Act 610 (the Water Well Drillers License Act).

## 5. Direct Push Technology

Direct Push Technology (DPT) devices are investigative tools that drive or 'push' small-diameter rods into the subsurface via hydraulic or percussive methods without the use of conventional drilling. DPT has been in use in the environmental industry for more than two decades and its utilization as a tool for performing subsurface investigations in Pennsylvania and many other states has grown concurrently with its evolving technology.

Monitoring wells installed using DPT could either be field-constructed, similar to conventionally drilled and installed wells, or installed using pre-packed well screens. The pre-packed well screen assemblies consist of an inner slotted screen surrounded by a wire mesh sleeve which acts as a support for filter media (sand). The sand is packed between the slotted screen and the mesh. It is important to note that only DPT pre-packed wells are considered suitable for Act 2 sites, due to quality assurance concerns regarding field-construction and associated problems placing the filter pack around the screens of small-diameter wells.

### a) Advantages of DPT

Depending on site conditions, DPT offers an attractive alternative to conventional auger drilling and split spoon sampling. The smaller size of DPT rigs enables well installation and sampling in areas not accessible to traditional large auger rigs.

As DPT methods utilize a smaller diameter boring than conventional drilling, less solid waste is generated. Similarly, less liquid waste will be generated from smaller diameter monitoring wells. Because less waste is generated, worker exposures are reduced.

Overall, there is minimal disturbance to the natural formation using DPT in comparison with auger drilling.

From an economic standpoint, DPT has several advantages versus conventional drilling. In relation to project schedule and budget, the time-effectiveness of DPT installation may enable the remediator to investigate more areas of a site than traditional hollow stem auger (HSA) drilling would allow and in a shorter time. Fewer well construction materials may enable a remediator to install additional monitoring points on a limited budget.

Most importantly, short-term and long-term groundwater monitoring studies conducted by others have produced results demonstrating that water samples collected from DPT installed wells are comparable in quality to those obtained from conventionally constructed wells.

### b) Disadvantages of DPT

DPT cannot completely replace the use of conventional drilling/monitoring well installation as limitations of the technology are evident in certain situations. DPT is only useful at generally shallow depths (less than 100 feet below surface grade) and in unconsolidated formations. DPT is not suitable for formations containing excessive gravel, cobbles, boulders, etc., or for bedrock drilling due to the obvious lack of augering capabilities.

DPT may be utilized for monitoring well installation below confining layers or as 'nested' wells with extreme caution. DPT utilizing only a macrocore barrel and drive rods may not provide for the advancement of casing to keep the borehole open and seal off each separate zone of saturation, which therefore can potentially allow for the mixing of separate zones of saturation when the push rods are withdrawn from the borehole. Therefore, DPT may be utilized for this purpose only if the project geologist can ensure that the threat of cross-contamination from separate zones of saturation above clean zones of saturation will not occur.

If large volumes of aqueous sample are required, DPT installed monitoring wells may not be suitable due to the small diameter of the well screen.

Since DPT causes smearing and compaction of the borehole sides, proper well development techniques are vital to ensure that natural hydraulic permeabilities are maintained. Several studies have demonstrated that hydraulic conductivities can vary by an order of magnitude lower for wells installed by DPT versus wells installed by conventional HSA. For this reason, DPT-installed wells may not be suitable for aquifer characteristics testing, nor for efficient groundwater recovery. Great care needs to be taken to ensure adequate well development when using DPT for well installations.

## 6. References

Aller, L., and others, 1989, Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells, National Water Well Association (This publication covers nearly all aspects of design and construction of monitoring wells. Each of the eight chapters has an extensive reference list.).

American Society for Testing and Materials, 2010, Standard Practice for Direct Push Installation of Prepacked Screen Monitoring Wells in Unconsolidated Aquifers, ASTM-D6725-04.

Anderson, K.E., 1993, Ground Water Handbook, National Ground Water Association (A quick reference containing tables, formulas, techniques and short discussions covering, among other things, drilling, well design, pipe and casing, and groundwater flow).

California Environmental Protection Agency, 2014, Well Design and Construction for Monitoring Groundwater at Contaminated Sites.

Driscoll, F.G., 1986, Groundwater and Wells, Second Edition, Johnson Filtration Systems, Inc., St. Paul, Minnesota 55112, 1089 pp.

Gaber, M.S., and Fisher, B.O., 1988, Michigan Water Well Grouting Manual, Michigan Department of Public Health (Very thorough coverage of grout and sealant formulation, characteristics, handling, and placement.).

Interstate Technology Regulatory Council, 2006, The Use of Direct Push Well Technology for Long-Term Environmental Monitoring in Groundwater Investigations.

Nielsen, D.M., (Editor), 1991, Practical Handbook of Ground-Water Monitoring, NWWA, Lewis Publishers, Inc., Chelsea, Michigan 48118, 717 pp.

Ohio Environmental Protection Agency, 2016, Technical Guidance for Ground Water Investigations, Chapter 15, Use of Direct Push Technologies for Soil and Ground Water Sampling, Revision 1.

U.S. Environmental Protection Agency, 1993, Subsurface Characterization and Monitoring Techniques-A Desk Reference Guide, Volume 1: Solids and Ground Water (Largely 1 to 2-page thumbnail descriptions of methods and equipment.).

U.S. Environmental Protection Agency, 1997, Expedited Site Assessment Tools for Underground Storage Tank Sites.

U.S. Environmental Protection Agency, 2005, Groundwater Sampling and Monitoring with Direct Push Technologies.

## C. Locations and Depths of Monitoring Wells

### 1. Importance

The locations and depths of monitoring wells are the most important aspects of a groundwater monitoring network. A monitoring point that is misplaced, or not constructed properly to monitor constituents with unique physical characteristics, is of little use and may misrepresent the quality of the groundwater migrating to or from a site. On the other hand, a properly positioned and constructed monitoring well that detects the earliest occurrence of contamination could save both time and money spent on cleanup of a site. It is important to note that the placement and construction of a groundwater monitoring network at an Act 2 site shall be conducted by a professional geologist licensed in Pennsylvania (25 Pa. Code §§ 250.204(a), 250.312(a), and 250.408(a)).

### 2. Approach to Determining Monitoring Locations and Depths

Different approaches and efforts for determining the location and depth of wells may be necessary based on the type of monitoring to be done. However, before well locations are chosen for any type of monitoring, the existing data should be evaluated. This can reduce the costs of implementing the monitoring program and can help to make appropriate choices for three-dimensional monitoring locations.

The most efficient way to accomplish the location and depth of monitoring wells for an Act 2 study is to formulate a CSM, or conceptual groundwater flow model. A conceptual groundwater flow model is the illustrative delineation and formulation of the important controlling components of groundwater flow and thus contaminant transport from recharge areas to discharge zones or withdrawal points. Without a proper conceptualization of groundwater flow, a groundwater model can give spurious results. On the other hand, a well-developed conceptual model may allow groundwater flow to be accurately approximated without using computer modeling or complex analytical procedures. The groundwater conceptual model is an important tool in the study of groundwater flow on both a local and even larger scale. The goal of the conceptual model is to represent the controlling aspects of groundwater flow at the site being investigated. Important controlling components of groundwater flow can include geological characteristics, geologic structural and stratigraphic relationships, anisotropy, calculated groundwater flow directions and recharge and discharge relationships.

Information may be obtained through site visits, site records and previous studies, interviews with present and past workers, aerial photographs, scientific publications on the local and regional hydrogeology, geophysical surveys, borings, wells, aquifer tests, etc. If enough information is available, the designer can determine the groundwater flow paths and design a complete monitoring network. However, actual testing of aquifer parameters and borehole geophysics provides the best information to evaluate placement and construction of monitoring wells, especially in newly established sites or facilities where little site information is available.

### a) Background Monitoring

The determination of background water quality is paramount in understanding the effect of an activity or site on groundwater quality. Often, insufficient site information is available so that initial well locations may depend on casual observations and assumptions regarding groundwater flow. If subsequent information shows that monitoring wells are misplaced, new wells should be installed.

### b) Site Characterization Monitoring

Appropriately placed monitoring wells are necessary to detect groundwater quality at an Act 2 site. The more that is known about the history of operations at the site, (potential) contaminant flow paths, and the constituents that may have been discharged to the environment, the more likely that monitoring wells installed during the site characterization phase of the investigation will be optimally placed and constructed to monitor the impact on groundwater quality. Monitoring well locations should be concentrated in those areas that will most likely first be impacted by the known discharges on the site, which typically will be located within or comprise the uppermost aquifer. As groundwater data is collected, additional monitoring wells may need to be installed to fully characterize the groundwater contaminant plume(s) present. The greater the complexity of the hydrogeology and the spread of contamination, the more monitoring wells that may be necessary to characterize the contamination.

### c) Attainment and Postremedial Monitoring

Any number of wells, including all installed during the site characterization phase, may be used for attainment monitoring. These wells will demonstrate attainment of the chosen cleanup standard at the POC. The impact of any remediation conducted at the Act 2 site on the groundwater flow paths (e.g. pumping the aquifer) should be considered for placement of attainment monitoring wells. Postremedial monitoring would likely be conducted in the same wells as attainment monitoring to monitor for any residual rebound occurring in the aquifer after remediation activities have been completed.

## 3. Factors in Determining Target Zones for Monitoring

The prime requirement for a successful monitoring system is to determine the “target” zones - the spatial locations and depths that are the most likely areas to be impacted by the site being investigated. The dimensions of target zones depend on the vertical and horizontal components of flow in the aquifers being monitored, the size of the Act 2 site, the potential contaminants released, and the distance that contamination may have traveled from the facility since being released. Figure A-4 shows how different target zones could be formed based on these factors.

Horizontal and vertical components of groundwater flow are best determined by constructing planar and cross-sectional flow nets based on the measurement of water levels in piezometers. Where the vertical components of flow are negligible, wells, rather than piezometers, drilled into the aquifer to about the same depth, will allow preparation of a contour map of water levels representing horizontal flow. This should be adequate to prepare a planar flow net and determine the target zone.

With regard to upgradient wells, target zones (as defined above) do not exist. Upgradient wells should be drilled to depths that are screened or open to intervals similar to that of the downgradient wells, or to depths that yield water that is otherwise most representative of the background quality of the water being monitored by the downgradient wells. In other words, upgradient wells should be installed within the same hydrogeologic aquifer to the respective downgradient wells.

The numerous site details to consider when establishing target zones may be grouped into either groundwater movement or the spatial distribution of contamination.

**a) Groundwater Movement**

In what direction is groundwater flowing? If flow paths are not easily determined, what will influence the direction of groundwater flow? The answers to these questions are critical to selecting target zones and the optimal locations of monitoring wells.

Using the groundwater levels from piezometers or wells at the site, the groundwater flow direction and hydraulic gradient can be determined. At least three monitoring points are needed to determine the horizontal flow direction and hydraulic gradient; however, at some sites, knowledge of the vertical component of flow may be important. This is best accomplished by using well pairs of "shallow" and "deep" piezometers or short-screened wells.

It may appear to be a simple task to place monitoring wells in downgradient positions using a map of the groundwater elevation contours, or by anticipating the flow direction based on topography or discharge points. However, at many sites, three-dimensional flow zones must be understood to install appropriate monitoring points (see Section C.5 of this appendix). Figure A-5 shows how a well can miss the vertical location of contamination at a site. Water level measurements, piezometer and well construction logs, geologic well logs, and groundwater flow direction maps should be reviewed carefully when assessing the dimensions of target zones.

**i) Geologic Factors**

The geology of a site can complicate the selection of the target zones for monitoring. Geologic factors can produce aquifers that are anisotropic. In an anisotropic aquifer, the hydraulic conductivity is not uniform in all directions so that groundwater moves faster in one direction than another and oblique to the hydraulic gradient. Anisotropy can result from various sedimentary or structural features such as buried channels, bedding planes, folds, faults, voids, and fractures.

In Pennsylvania, most of groundwater flow in bedrock is through fractured rocks. Fracture flow in bedrock (or hardened sediments) requires additional considerations compared to flow in unconsolidated materials. Consolidated materials may exhibit small effective porosities and low hydraulic conductivities that impede groundwater flow. However, the development of secondary porosity may allow substantial flow of groundwater through fractures, joints, voids, cleavage planes and foliations. These features tend to be highly directional, exhibit varying degrees of interconnection, and may produce local groundwater flow regimes that are much different from the regional trends.

Geologic factors influence the direction of groundwater flow by controlling the transmissivity. For example, Figure A-6 shows the effect of fractures on the spread of contamination. Although the gradient indicates flow to the north, groundwater also follows the major fractures and spreads to the northeast. Monitoring wells "1" and "2" located to the north of the site may detect contamination, but the lack of a monitoring well to the northeast will miss an important direction of migration. Common sedimentary bedding planes also could have a similar effect on groundwater flow.

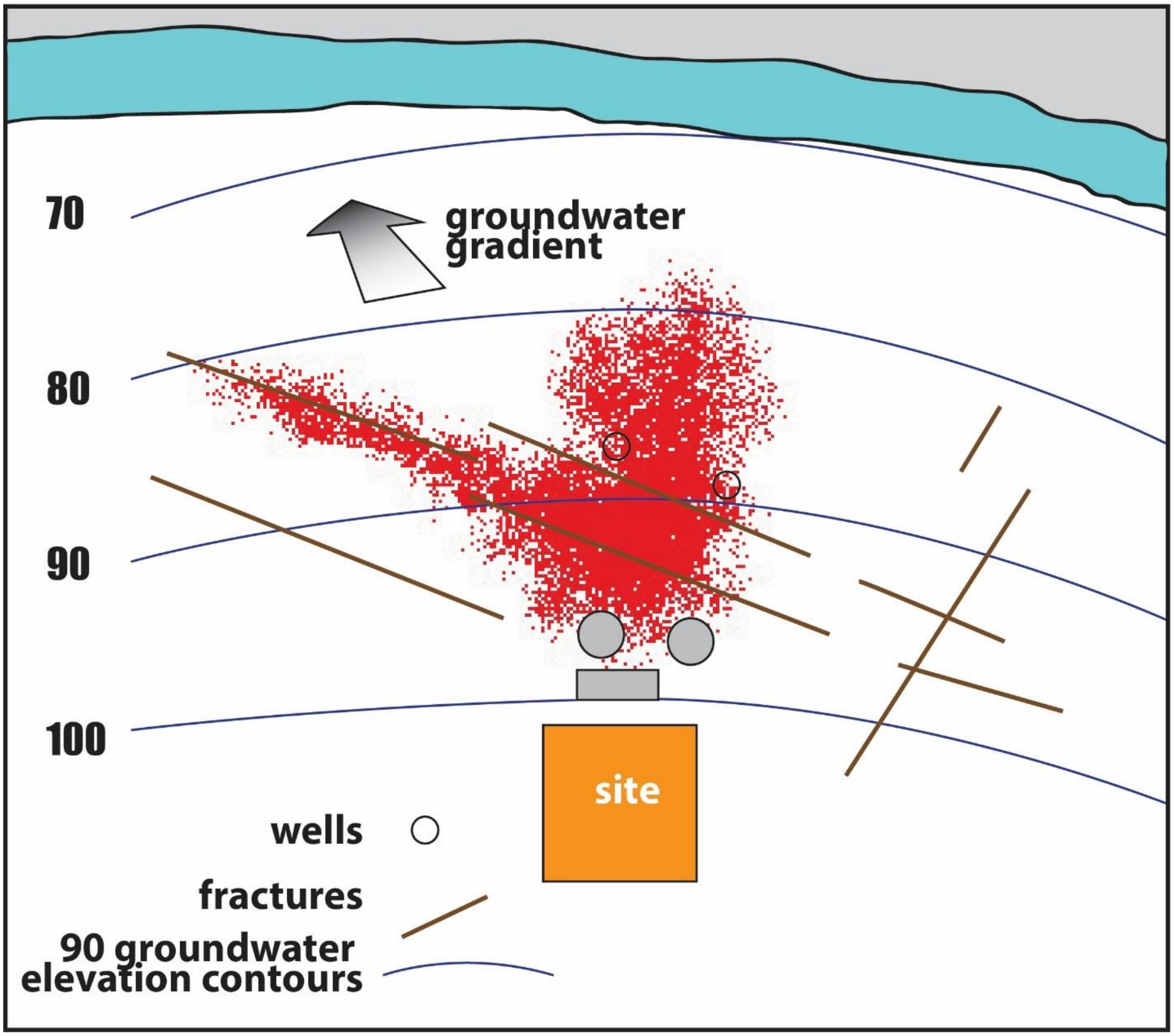
It is important to identify hydrostratigraphic intervals which may or may not be interconnected at the site when conducting a groundwater investigation. Monitoring wells should not be screened across two intervals as groundwater flow and concentrations of contaminants may differ significantly in each interval.

**ii) Groundwater Barriers**

The presence of hydrogeologic barriers should also be considered when locating wells in a groundwater monitoring system. A groundwater barrier is a natural geologic or artificial obstacle to the lateral movement of groundwater. Groundwater barriers can be characterized by a noticeable difference in groundwater levels on opposite sides of the barrier. Geologic faults and dikes along with tight lithologic formations such as shale and clay layers are common examples. Important types of barriers include the following:

<u>Geologic faults</u> - Fault planes that contain gouge (soft rock material) or bring rock bodies of widely differing hydraulic conductivity into juxtaposition can influence groundwater flow direction and velocity. Location of downgradient wells across fault zones or planes should not be approved until the nature of the influence of the fault zone on groundwater flow has been evaluated. One method of evaluating fault zones is to conduct pumping tests with wells on either side of the fault plane to evaluate the degree of hydraulic connection.

**Figure A-6: Effect of Fractures on the Spread of Contamination**



Dikes - Diabase dikes, common in southeastern Pennsylvania, can function as lithologic barriers to groundwater flow because of their very low permeability. If a dike lies between a site and a proposed downgradient well, the role of the dike should be evaluated prior to approving the well's location.

Others - Geologically "tight" layers (aquitards) or formations can function in a similar way: they can create subsurface "dams" that cause groundwater to flow in unexpected directions. Additional barriers to flow can include inclined confining beds, groundwater divides, and artesian aquifers.

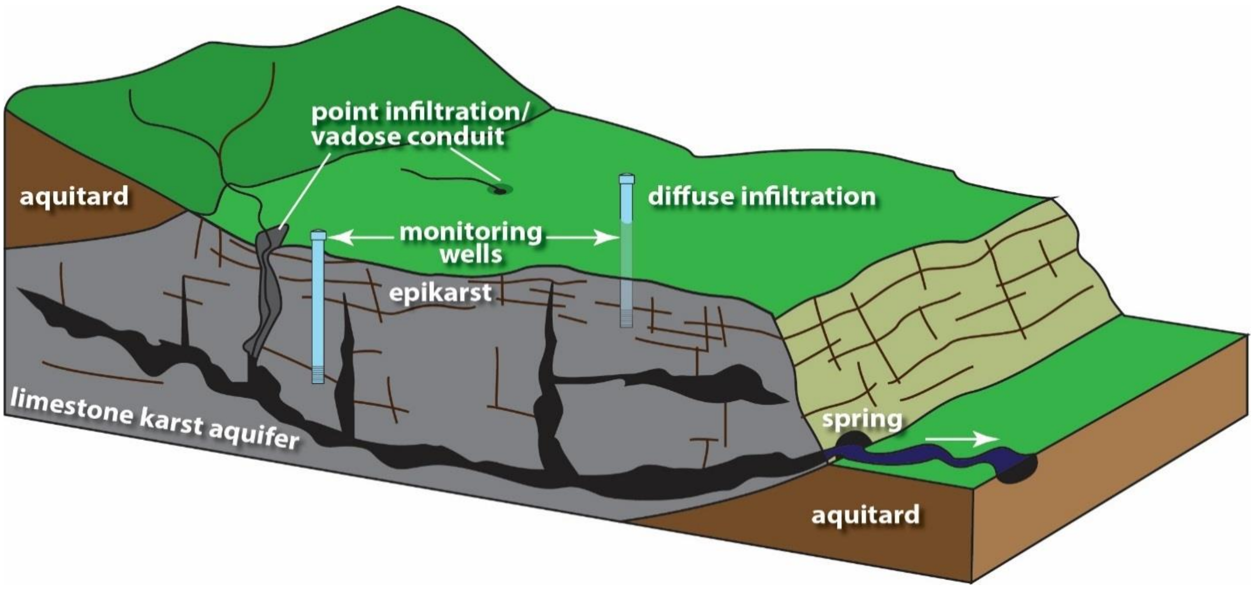
**iii) Karst Terrane**

Carbonate rock such as limestone and dolomite is susceptible to the formation of sinkholes, solution channels, and caverns. In Pennsylvania, almost all carbonate rock will exhibit some degree of karst development. Resulting flow patterns can be very complicated; flow depends on the degree of interconnection of the joints, fractures, and solution openings (small and large), the hydraulic gradient, and geologic barriers. The resulting anisotropic setting can make it difficult to effectively monitor and model a site in a karst area. Even a relatively small cavernous opening with its connecting drainage paths can control a significant amount of the flow from an area, and may perhaps effectively carry all the groundwater that discharges from underneath a site. In addition, karst geology has the potential to rapidly transmit groundwater over a large distance.

Groundwater flow in a karst terrane can be highly affected by precipitation events, and groundwater divides can be transient. To determine monitoring locations in limestone and dolomite areas, the remediator should investigate the degree to which the rocks are susceptible to dissolution. The more dissolution features that are recognized, the more likely that conduit flow will occur. Dissolution features may be identified through site visits, aerial photographs, geologic well logs, and geophysical techniques.

Thus, it would seem logical that monitoring locations should be based on major conduits of flow. However, Figure A-7 shows how a monitoring well can easily miss a primary conduit. It may be futile to attempt to establish the locations of such flow zones because they probably represent only a small fraction of a site. However, several procedures can be used to increase the odds of monitoring the site of concern. (Note that many of the procedures discussed here also can be used in other types of fractured rocks.)

**Figure A-7: Ineffective Monitoring Wells in a Carbonate Aquifer**




Tracer tests - Tracer tests offer the best possibility of determining where groundwater is flowing and discharging. They are conducted to establish a hydraulic connection between a downgradient monitoring point and the facility of concern. Tracer tests should be combined with a thorough inspection for the presence of local and regional springs, surface streams, and dry stream channels that could serve as discharge points for groundwater at the site. It also could be possible that groundwater beneath a site could discharge to several features, or that the flow directions could be different during flood or high groundwater stages. A determination of the point of regional base flow should also be made and possibly included as a monitoring point when possible.

It is important to understand the potential chemical and physical behavior of the tracer in groundwater. The objective is to use a tracer that travels with the same velocity and direction as the water and does not interact with solid material. It should be easily detected and be present in concentrations well above natural background quality. The tracer should not modify the hydraulic conductivity or other properties of the medium being studied. Investigations using tracers should have the approval of local authorities and the Department, and local citizens should be informed of the tracer injections.

Various types of tracers are used including water temperature, solid particles, ions, organic acids, and dyes. Fluorescent dyes are the most common type of tracer used in karst areas. These dyes are used because they are readily available, are generally the most practical and convenient tracers, and they can be adsorbed onto activated coconut charcoal or unbleached cotton. Fluorescent dyes can be detected at concentrations ranging from one to three orders of magnitude less than those required for visual detection of non-fluorescent dyes. This helps to prevent the aesthetically unpleasant result of discoloring a private or public water supply.

Fluorescein (CI Acid Yellow 73 - $C_{20}H_{10}O_5Na_2$) is one of the most widely used water-tracers in karst terrane studies because of its safety, availability, and ready adsorption onto activated coconut charcoal. It is a reddish-brown powder that turns vivid yellow-green in water, is photochemically unstable, and loses fluorescence in water with pH less than 5.5.

Rhodamine WT is another commonly used dye tracer. Rhodamine WT is a conservative dye and generally efficient tracer because it is water soluble, highly detectable (strongly fluorescent), fluorescent in a part of the spectrum not common to materials generally found in water, thereby reducing the problem of background fluorescence, harmless in low concentrations, inexpensive, and reasonably stable in a normal water environment (U.S. EPA 2013).

The toxicity of the dyes should also be considered, especially when there is a chance of private or public water supplies being affected. Smart (1984) presents a review of the toxicity of 12 fluorescent dyes. Other excellent references include U.S. EPA and the USGS (1988) and Davis and others (1985).

The mapping of outcrops and associated joints and faults can distinguish directional trends that groundwater might follow. Fracture trace analysis using aerial photographs can detect local and regional trends in fractures, closed depressions, sinkholes, stream alignments, and discharge areas. However, tracer tests are still recommended to verify where groundwater is flowing.

Additional site investigation techniques may be helpful in determining flow paths. Geophysical methods such as self-potential (a surface electromagnetic method) and ground penetrating radar can enhance the understanding of karst systems.

Effort should be made to monitor at or near the site of concern rather than depend on springs that discharge away from the site. Wells sited on fracture traces or other structural trends can be tested with tracers to see if they intercept groundwater flowing from the site. A monitoring network should not be solely dependent on water levels to establish the locations of monitoring wells in such fractured rock settings. These uncertainties and the potential traveling distances may cause monitoring in karst areas to be involved and expensive.

For more information regarding tracer tests, please refer to the USGS website on tracer studies.

#### iv) Deep-Mined Areas

When designing a groundwater monitoring program for a site in which coal or noncoal deep mining has occurred, it is important to consider the effect of the underlying mine on the hydrologic system.

Because of the mine workings and the associated subsidence fractures, the deep mine often acts as a large drain for the overlying water-bearing zones. Groundwater monitoring of this zone may be considered on a case-by-case basis.

Saturated zones within deep mines may be characterized as a mine pool, which is a body of water at a relatively stable elevation, or it may be a pathway for channelized water. Because of these special problems, a drilling plan should be devised that includes provisions for drilling through the coal pillar, mine void or collapsed structures. Several attempts should be made at each well location to intercept the pool, saturated zone and/or mine void.

Well construction requires the placement of a grout basket or plug attached to the riser pipe that is placed above the zone to be monitored. This helps to seal the bentonite grout.

### b) Contaminant Distribution

In addition to normal groundwater flow (advection), the distribution of contamination is critical to the correct placement of monitoring points. This distribution is based on 1) the chemical and physical characteristics of groundwater and contaminants present that affect the migration of the monitored contaminant, and 2) its occurrence or source at the site. For example, the density of a contaminant is one of the most important factors in its distribution in the aquifer, and especially for determining the depth of a target zone (see Section C.5 of this appendix). Petroleum hydrocarbons tend to remain in shallow groundwater. Chlorinated VOCs tend to migrate deeper into the aquifer, sometimes following structural features that may be contrary to groundwater flow direction. These factors are extremely important to consider when designing a groundwater monitoring network.

Isoconcentration maps can be useful in plume interpretation and for placement of groundwater recovery wells. Also, the remediator should keep in mind the relationship of the flow lines with the activity’s location or potential sources of contamination.

## 4. Areal Placement of Wells

For establishing the target zones, the remediator should consider the topics of groundwater movement and contaminant distribution that were discussed above. For the initial placement of wells at a site where little information is available, the downgradient well positions are typically assumed to be downslope. In apparent flat-lying sites, drainage patterns can be used to estimate the flow direction. The site boundary that is closest to a body of water is a likely choice for downgradient well locations. An upgradient well is typically placed upslope.

As more information is obtained about the site, groundwater gradients will be more accurately defined. Upgradient and downgradient monitoring points may need to be added or moved. However, even well-defined groundwater flow direction maps should be evaluated carefully when choosing the target zones for upgradient and downgradient wells. Because of structural controls in fracture flow described in Section C.3.a, groundwater can move obliquely to the regional gradient. Some monitoring points may need to be moved as target zones are refined.

In general, when comparing sites, intervals between monitoring wells probably should be closer for a site that has one or more of the following:

- a small area
- complicated geology such as folding, faulting, closely spaced fractures, or solution channels
- heterogeneous lithology and hydraulic conductivities
- steep or variable hydraulic gradient
- high seepage velocity
- had liquid contaminants
- tanks, buried pipes, trenches, etc.
- low dispersivity potential

Sites without these features may have well interval distances that are greater. See also Section C.6 on the number of wells.

Reconnaissance tools and screening techniques such as surface geophysical techniques and soil gas studies can help to locate plumes before wells are drilled and thus help to determine optimal well locations. Methods for selecting sample locations range from random yet logical picks to probability sampling (such as a grid pattern). Random sampling is very inefficient. When selecting many monitoring points in an area where little is known, such monitoring points should be placed in a grid or herringbone pattern.

## 5. Well Depths, Screen Lengths, and Open Intervals

The first zone of saturation is typically an unconfined or water-table aquifer, which is recharged from direct infiltration of precipitation. Impacts to the aquifer under unconfined conditions are more easily evaluated than under confined or semi-confined conditions. The shallowest aquifer should be the target zone for chemicals and substances that are less dense than water.

Sites with confined aquifers that have the potential to be impacted will need to be evaluated in combination with the unconfined aquifer.  Such a situation would require more detailed vertical and discrete zone monitoring.

Once the subsurface geometry of the monitoring target zone is determined, decisions can be made with respect to the depth and screen lengths of individual wells that will be used. Groundwater monitoring networks should monitor the entire saturated thickness of the target zone, or a very large percentage of it.  If large vertical intervals of the target zone are unmonitored, chances are dramatically increased that groundwater contamination may go undetected or be underestimated if detected.

Choosing the length of the open interval in a monitoring well is in many respects a balancing act.  Shorter open intervals or screen lengths provide better accuracy in determining hydraulic head at a specific point in the flow system.  If a sufficient number of shorter well screens or open intervals are stacked or clustered vertically so that the entire saturated thickness of the target zone is adequately monitored, they will, when taken together, provide better resolution of the vertical distribution of any contamination that may be detected.  In addition, the possibility of cross-contamination is minimized. Disadvantages of shorter intervals include reduced water volume from each well and the increased cost of installing, sampling, analyzing, and interpreting the data from the more numerous sampling points, which can be considerable.

Some disadvantages also are likely for longer screen lengths or open intervals. Resolution of hydraulic head distribution in the aquifer decreases, contamination entering the well at a specific point may be diluted by other less contaminated water, and there is less certainty regarding where water is entering the well.

It would be preferable from a strictly technical point of view to monitor the entire saturated thickness of any target zone with a number of individual, shorter-screened wells drilled to different depths that, together, monitor the entire target zone.  However, the remediator/hydrogeologist designing the project must decide if the increased cost over single, longer-screened wells is justified for background and compliance monitoring. The goal is to establish screens and open intervals that will detect any contamination emanating from any portion of the site as quickly as possible.  A Pennsylvania-licensed professional geologist should make all decisions related to the construction of monitoring wells at Act 2 sites.

Care should be taken when monitoring target zones in bedrock formations.  In this case, by geologic necessity, the portion of the target zone which is monitored will be determined by the location and number of water-producing fractures that are intercepted by the well.  Care must be taken not to drill wells too deeply below the target zone in search of a water-producing fracture.

Where multiple aquifers exist, such as an unconsolidated aquifer overlying a bedrock aquifer, or where two permeable aquifers are separated by a confining layer, the target zones within each aquifer should be monitored separately.

The specific gravity of a contaminant and whether it will most likely be introduced to the environment as a free phase or in a dissolved phase also will influence how a well is constructed. In conducting monitoring for an LNAPL or a petroleum-based dissolved contaminant, such as gasoline, wells should be constructed with screens, or open intervals, that intercept the water table surface at all times of the year during periods of both high and low water table elevations. LNAPL can then accumulate into a distinct layer and flow into the monitoring well. For materials that exhibit specific gravities greater than water (such as many chlorinated solvents), it is desirable, though not always possible, to locate subsurface boundaries on which such contaminants might accumulate if released to the environment in a free phase.

## 6. Number of Wells

The number of wells needed depends on site-specific factors. In general, the spacing of background or upgradient wells should be adequate to account for any spatial variability in the groundwater quality. Downgradient wells should be positioned to adequately monitor the activity and any other variability of the groundwater quality. Compliance wells should be considered downgradient wells and positioned as close to the downgradient boundary of the site. The estimate of the separation distance will depend on the extent and type of activity, the geology, and the potential contaminants (see also Section C.4 on the Areal Placement of Wells).

## 7. Well Yield

Monitoring wells should produce yields that are representative of the formation in which they are drilled. Wells located in anomalously low-yielding zones are undesirable for several reasons. First, flow lines tend to flow around low-permeability areas rather than through them. In effect, this results in potential contaminants bypassing low-permeability areas, consequently not being detected in representative concentrations. In addition, by the time a potential contaminant shows up in a very low-yielding well that is unrepresentative of the formation, other potential contamination may have traveled extensively downgradient beyond the monitoring well. Therefore, in settings where well yields are variable, the best monitoring wells will be those that are open to the highest permeability flow lines that are potentially more likely to be contaminated by the site.

The best information regarding representative yield for the target zones selected for any site should come from the wells and borings used in the investigation to characterize the groundwater flow system for the site. Borehole geophysics can be a valuable tool for determining the location of higher-yielding zones and the presence of contaminants. For more detailed descriptions of borehole geophysical techniques and devices, see EPA (1993) Chapter 3 - Geophysical Logging of Boreholes, and Nielsen (1991). Additional regional hydrogeologic information may be obtained from:

- The Pennsylvania Bureau of Topographic and Geologic Survey (BTGS)
- The United States Geological Survey (USGS)

Water Resource Reports have been published by the USGS and BTGS for select counties and areas in Pennsylvania. Many of these reports are available electronically on their respective websites.

In Pennsylvania, there are three general hydrogeologic settings that merit special discussion from a well-yield perspective.

**a) Fractured Rock**

In aquifers composed of fractured bedrock, groundwater flow is generally restricted primarily to the fractures. If a well fails to intersect any fractures or a very few small fractures in this setting, the well will not detect potential contamination, or it will be inefficient in detecting potential contamination. For this reason, wells that fail to intersect fractures in the target zone that are representative of the formation should be approved with caution, and wells that are essentially dry are not acceptable. Such wells should be relocated nearby and another attempt made to obtain a better yield when it is determined that it is likely that more representative yields can be obtained. Likewise, wells drilled below the proper target zone, strictly to increase yield, are not reliable for site characterization purposes.

**b) Heterogeneous Unconsolidated Formations**

Low permeability, clay-rich formations with interbedded or lenticular, higher permeability sand or gravel units can present a significant challenge to designers and installers of monitoring wells. Wells need to be located so that they are open to any high permeability zones within the target zone that are hydraulically connected to the site being monitored. These wells will produce a higher yield than wells drilled exclusively into the clay-rich portions of the site.

**c) Areas of Uniformly Low Yield**

Certain geologic formations and hydrogeologic settings are characterized by exhibiting naturally low yield over a wide area. Other geologic formations may exhibit low yield locally in certain settings such as ridge tops, steeply dipping strata, or slopes. In these settings, a permanent or seasonal perched water table or shallow flow system may develop on the relatively impermeable bedrock that may or may not be hydraulically connected to the bedrock system. Depending on the permeability of the soils and unconsolidated material overlying the solid, less permeable bedrock, the shallow groundwater flow can express itself as a rather rapid "subsurface storm flow" or a more sluggish, longer-lasting condition in poorly drained soils.

It is important to be sure that the shallow systems are part of the target zone of the site being monitored. In these cases, the shallow system may constitute the most sensitive target zone for monitoring a facility. While wells drilled into the bedrock system may be needed to monitor for vertical flow of contaminants, the importance of sampling monitoring wells or springs in the shallow intermittent flow system should not be underestimated, although the usual periodic monitoring schedules may not always be necessary in these settings. If the systems are intermittent, one must be aware of when they are active (e.g. in Spring or after significant or extended precipitation events) and be prepared to monitor the systems at that time. Monitoring can be conducted in wells, springs that are properly developed, or in some cases, by sampling man-made underdrain systems that are constructed to collect the shallow flow system in some cases.

## 8. References


Davis, S.N. and others, 1985, Ground Water Tracers, through the U.S. EPA. Cooperative Agreement CR-810036.

Dobrin, M.B., 1965, Introduction to Geophysical Prospecting, 3rd ed., McGraw-Hill, New York, 583 pp.

Everett, L.G., 1980, Groundwater Monitoring, General Electric Company, 440 pp. [Note Section 2 ("Groundwater Monitoring Methodology") and Section 4 ("Monitoring in the Zone of Saturation")].

Ferguson, Colin, June 1992, The Statistical Basis for Spatial Sampling of Contaminated Land, Ground Engineering, pp. 34-38.

Fetter, C.W. Jr., Fall 1981, Determination of the Direction of Ground Water Flow, Ground Water Monitoring Review, pp. 28-31 (Discusses anisotropy in groundwater flow.).

Giddings, Todd and Shosky, D.J. Jr, Spring 1987, Forum - What is an Adequate Screen Length for Monitoring Wells? Ground Water Monitoring Review, pp. 96-103 (Pros and cons of screen lengths.).

Grant, F.S. and West, G.F., 1965, Interpretation Theory in Applied Geophysics, McGraw-Hill, New York, 583 pp.

Interstate Technology Regulatory Council, April 2015, Integrated DNAPL Site Characterization and Tools Selection.

Kurtz, David and Parizek, R., 1986, "Complexity of Contaminant Dispersal in a Karst Geological System," in Evaluation of Pesticides in Ground Water, American Chemical Society, Symposium Series, vol. 315, pp. 256-281.

Nielsen, D.M., (Editor), 1991, Practical Handbook of Ground-Water Monitoring, NWWA, Lewis Publishers, Inc., Chelsea, Michigan 48118, 717 pp (Note especially Chapter 2 on "Ground-Water Monitoring System Design" by Martin Sara.).

Ohio Environmental Protection Agency, 2015, Technical Guidance Manual for Groundwater Investigations, Chapter 3, April 2015.

Pfannkuch, H.O., Winter 1982, Problems of Monitoring Network Design to Detect Unanticipated Contamination, Ground Water Monitoring Review, pp. 67-76 (Discusses contamination release, propagation, and monitoring stages of unexpected releases.).

Quinlan, J.F., 1990, Special problems of ground-water monitoring in karst terranes: Ground Water and Vadose Zone Monitoring, ASTM Special Technical Paper 1053, pp. 275-304.

Quinlan, J.F., 1989, Ground-Water Monitoring in karst terranes: Recommended protocols and implicit assumptions: US EPA, EPA/600/X-89/050, 78-pp.

Saines, M., Spring 1981, Errors in Interpretation of Ground Water Level Data, Ground Water Monitoring Review, pp. 56-61 (Identifies common errors.).

Smart, D.L., 1984, A review of the toxicity of twelve fluorescent dyes used for water tracing: National Speleological Society Bulletin, v. 46, no. 2, pp. 21-33.

U.S. Environmental Protection Agency, September 1986, RCRA Ground Water Monitoring Technical Enforcement Guidance Document (Note Chapter 2, “Placement of Detection Monitoring Wells.”).

U.S. Environmental Protection Agency and the U.S. Geological Survey, October 1988, Application of Dye-Tracing Techniques for Determining Solute-Transport Characteristics of Ground Water in Karst Terranes, EPA 904/6-88-001 (Note especially Chapter 2: “Hydrogeology of Karst Terrane.”).

U.S. Environmental Protection Agency, May 1993, Subsurface Characterization and Monitoring Techniques - A Desk Reference Guide, Volume 1: Solids and Ground Water. EPA/625/R-93/003a (Complete description of geophysical techniques and their advantages and disadvantages is included. Also, aquifer tests and sampling methods are presented.).

U.S. Environmental Protection Agency, Science and Ecosystem Support Division, May 2013, Dye Tracer Measurements. SESDPROC-514-R1.

U.S. Geological Survey, 1997, Guidelines and standard procedures for studies of ground-water quality: Selection and installation of wells, and supporting documentation, Water-Resources Investigations Report 96-4233.

Wilson, C.R., Einberger, C.M., Jackson, R.L., and Mercer, R.B., 1992, Design of Ground-Water Monitoring Networks Using the Monitoring Efficiency Model (MEMO), Ground Water, v.30, No.6, pp. 965-970.

## D. Groundwater Sampling Techniques

### 1. Importance of Sampling Technique

Proper sampling procedures which result in a representative measure of groundwater quality are critical to any monitoring program. The accuracy of the sample analysis in the laboratory is dependent upon the sampling methodology in the field. A laboratory cannot generate reliable data if the sample was collected improperly. Therefore, taking precautions and selecting the correct sampling methods are imperative to produce accurate and representative analyses.

Some of the reasons groundwater samples may not be representative of aquifer conditions include the following:

- The sample was taken from stagnant water in the well. Water standing in a well and exposed to the atmosphere may undergo a gas exchange (oxygen and carbon dioxide), allowing chemical reactions to occur. Biological organisms capable of driving reactions might also be introduced. Obviously, such altered waters will no longer be representative of the water within the aquifer and therefore should be purged prior to sample collection.

- The sample was not collected at the appropriate time. The sample should be collected as soon as possible after purging is completed. This reduces the possibility of chemical reactions occurring because of gas exchange and temperature variations. In addition, if the well is pumped too long, the sample may be comprised of water far from the well site and not be representative of groundwater chemistry for the site being monitored.

- The sample contained suspended or settleable solids. Groundwater is generally free of suspended solids because of the natural filtering action and slow velocity of most aquifers. However, even properly constructed monitoring wells will often fail to produce samples that are free of sediment or settleable solids (turbidity). When samples containing suspended solids are analyzed for metals, this sediment is digested (dissolved) in the laboratory prior to performing the analysis. Consequently, any of the metals present in the sediment (primarily iron, manganese, and aluminum) will be included in the results of the analysis of the water that includes these metals. The analysis of the water samples containing sediment will result in certain analytes, such as these metals, being reported at higher levels than the actual levels in groundwater.

In addition to common metals, other metals such as lead, chromium, arsenic, and cadmium, which occur naturally in trace amounts may also show up in the analysis. Additionally, the sediment content of the monitoring wells will often vary across a site, so that samples collected from the same well at different times can vary in sediment content. This problem can make analysis of monitoring well data for metals where samples have not been filtered to remove turbidity an almost futile exercise.

- Release of carbon dioxide during pumping increased the pH, allowing many metallic ions to come out of solution (i.e. iron, manganese, magnesium, cadmium, arsenic, selenium, and boron). Pumping can also cause volatilization of VOCs. This emphasizes the importance of conducting field measurements such as pH, specific conductance, temperature, etc., within the well before the sample is brought to the surface.

- Chemical changes occurred from oxidation of the sample during sampling. Dissolved oxygen is usually very limited within aquifers. Bringing the sample to the surface allows oxygen to dissolve within the water sample. Oxidation also can occur in the pump, or it can be caused by water cascading into a well installed in "tight" formations. Depending on the chemical makeup of the sample, the addition of dissolved oxygen may allow chemical reactions to occur. Some of the changes that can be expected include oxidation of: 1) organics, 2) sulfide to sulfate, 3) ferrous iron and precipitation of ferric hydroxide, 4) ammonium ion to nitrate, and 5) manganese and precipitation of manganese dioxide or similar hydrous oxide. In cases where oxidation would be expected to impact chemical quality, precautions should be employed to reduce oxidation potential (e.g. minimize agitation during purging and sample collection, minimize the length of time the sample is exposed to air, fill the sample container completely to the top, and promptly chill the sample).

- The sample was not preserved correctly. Increases in temperature will allow certain chemical reactions to occur. Certain metals, especially iron, may coat the inside of the sample container. If the sample is not properly preserved for shipment to the laboratory, the sample arriving at the lab may be quite different chemically from the sample which was collected in the field.

- The sample was contaminated by residues in sampling equipment. Residues may cling to the sampling equipment if it is not properly cleaned or decontaminated. Those residues may become mobile in successive samples, yielding unreliable results. This becomes critical when the analytes being sampled are in the parts per billion or parts per trillion range. As a result, all sample pumps, tubing, and other associated materials should be properly decontaminated prior to sampling at each monitoring well location.

- The sample was contaminated by the mishandling of bottleware. Care should be taken to avoid contamination by mishandling bottleware, whether in the field or during transport. All sample bottleware and coolers should be stored and transported in clean environments to avoid potential contamination. In addition, care should be taken when storing and transporting bottleware that already contains a preservative. For example, the preservative may leak from a sample bottle or be altered by extreme heat or cold.

- The sample was contaminated by residuals on the hands of the sampler. To avoid contamination that may result from bare skin, protective sampling gloves should be worn during sample collection. New gloves should be worn for each well location.

DEP recommends utilizing a consistent sampling methodology throughout the monitoring program.

## 2. Sample Collection Devices

The most common devices available for the collection of water from monitoring wells include bailers, suction-lift pumps, air-lift samplers, bladder pumps, submersible centrifugal pumps, and passive samplers. Each has its advantages and disadvantages, as shown in Table A-1, and should be considered before selecting the sample collection device.

## 3. Sample Collection Procedures

The following are general procedures that should serve as a framework for sampling groundwater. These procedures should be modified as necessary for each situation encountered in the field and to conform to monitoring objectives. In addition, appropriate health and safety measures should always be taken before, during, and after sampling.

### a) Protective Clothing

Protective clothing should be worn as dictated by the nature of the contaminants. Different types of protective clothing are appropriate for different contaminants. Protective sampling gloves should always be worn during sample collection to ensure a representative sample and to protect the sampler.

### b) Water Levels

Every effort should be made to determine and record the static water level of the well prior to purging. Static water levels should be recorded in each well prior to any well purging when part or all of a groundwater monitoring network is sampled in one event. Water level measurements should also be measured and recorded during well purging to document associated drawdown.

### c) Field Measurements

In most cases, field measurements should be taken before and during the sampling to gauge the purging of the well and to measure any changes between the time the sample is collected compared to when it is analyzed in the laboratory. Measurements in the field also provide a record of actual, onsite conditions that may be useful for data analysis. The following measurements and observations are often determined in the field:

- pH
- Eh
- water level (static and purged)
- temperature

- specific conductance
- dissolved oxygen
- acidity/turbidity
- climatic conditions

The specific techniques for obtaining each of these measurements depend upon the instruments used. The operator should carefully read and follow the manufacturer's instructions, including those for equipment maintenance and calibration. A record of the calibration and maintenance checks should be kept. Field measurements should always be made with properly calibrated instrumentation.

**d) Purging**

The purpose of purging a well prior to sampling is to remove stagnant water from the well bore and assure that the sample is representative of the groundwater in the geologic formation. Stagnant water in the well bore results from the water's contact with the casing and atmosphere between sampling events. What might seem to be a relatively simple and straightforward procedure, purging technique has been the subject of considerable scientific investigation and discussion.

There are two basic approaches to purging a well. The first is to use dedicated equipment in which the water is pumped from a fixed position in the well. This technique eliminates the possibility of cross-contamination, but tends to purge only the well section, or screen section opposite of the purge pump. (This is especially a concern when purge rates are much lower than the yield of the water-bearing zone supplying water to the purge pump.)

The second basic approach is to use a transportable pump and purge from the water surface, or preferably by gradually lowering the pump in the well as stagnant water is evacuated. This technique is considered as being more reliable in terms of evacuating the entire well bore. However, the disadvantage is that the equipment must be decontaminated between wells, which in turn increases the potential for cross-contamination.

It is important to recognize the impact of equipment location in relation to the well and other sampling equipment. Often purging and sampling equipment require the use of generators to power pumps and other equipment. The engines of vehicles and generators produce exhausts which contain VOCs as well as various metals and particulates. If engines or generators need to be operating while sampling, they should be located upwind from the well and sampling equipment since water contacting these exhausts has been shown to contaminate samples with various compounds.

**Table A-1: Advantages and Disadvantages of Different Sampling Devices**

| | ADVANTAGES | DISADVANTAGES |
|---|---|---|
| Bailer | Portable<br><br>Simple to use<br><br>No need for an electrical source | Difficult to ascertain where within the water column the sample is collected<br><br>Allows for oxidation of the sample<br><br>Disturbance of the water column by the sampler<br><br>Impractical for removing large volumes of water |
| Suction-lift Pump | Allows sample to contact only Teflon (less decontamination)<br><br>Very portable<br><br>Simple to use for shallow applications<br><br>Flow rates easily controllable | Limited to shallow groundwater conditions (approximately 30 feet)<br><br>Causes sample mixing, oxidation, and allows for degassing<br><br>Not ideal for collection of gas-sensitive parameters |
| Air-lift Sampler | Suited for small diameter wells | Causes extreme agitation<br><br>Significant redox, pH, and specie transformations<br><br>Plastic tubing source of potential contamination |
| Bladder Pump | Provide a reliable means for highly representative sample<br><br>Mixing and degassing minimized<br><br>Portable<br><br>Noted by EPA as an excellent sampling device for inorganic and organic constituents | Somewhat more complex than other samplers<br><br>Turbid water may damage the inner bladder<br><br>Water with high suspended solids may damage check valves |

| | ADVANTAGES | DISADVANTAGES |
|---|---|---|
| Submersible Centrifugal Pump | Higher extraction rates | Considerable agitation and turbulent flow<br><br>Potential to introduce trace metals from the pump materials |
| Passive Samplers | Low cost<br><br>Easily deployed<br><br>Minimal purging and water disposal<br><br>Able to monitor a variety of analytes | Some devices are incompatible with certain analytes.<br><br>May have sample volume limitations.<br><br>Results may differ from conventional methods. |

An excellent summary of purging methods and techniques is given by Herzog et al. (in Nielsen, 1991). The following discussion is based in part on that summary. Four techniques for determining the volume of water to be purged from a well are discussed. These techniques include criteria based on:

- Numbers of well bore volumes
- Stabilization of indicator parameters
- Hydraulic and chemical parameters
- Special problems with low-yielding wells

By far, the most common choices have been to base the purging volume on either a certain number of well volumes, or stabilization of chemical and physical parameters, or some combination of these two.

An alternative approach, also described below, eliminates purging the well altogether by using passive sampling devices.

**i) Criteria Based on the Number of Bore Volumes**

The purging of three well volumes was universally accepted at one time and ingrained in monitoring practice. However, Herzog et al., provides references from numerous studies which conclude that anywhere from less than one to more than 20 bore volumes might variously be purged from wells prior to being acceptable for sampling. Herzog, et al. conclude:

"It is obvious that it is not possible to recommend that a specific number of bore volumes be removed from monitoring wells during purging. The range of suggested volumes is too large and the cost of improper purging is too great to permit such a recommendation."

DEP recommends that if the borehole volume technique is going to be used, the number of borehole volumes required for each well should have a technical or scientific basis, such as stabilization of indicator parameters (see following section) conducted at least once for each well during initial sampling events, rather than being based on some arbitrary criterion such as "three well volumes."

When purging is based on some set number of borehole volumes, the borehole volume calculation should take into account the entire original borehole diameter, corrected for the porosity of any sand or filter pack, and not be based just on the innermost casing diameter.

**ii) Criteria Based on Stabilization of Indicator Parameters**

Stagnant water in a well bore differs from formation water with respect to many parameters. Field measurement of indicator parameters such as temperature, pH, specific conductance, dissolved oxygen, and Eh has been used as the criteria for determining the amount of water to purge and when to sample a well. These parameters are measured in the purge water during purging until they reasonably stabilize. DEP encourages the use of this method.

DEP recommends that all of the above indicators be measured during the initial and first few sampling events for the monitoring well. The data should then be reviewed to determine which indicator parameters are the most sensitive indicator that stagnant water has been evacuated from the well. The most sensitive parameters will be those showing the greatest changes and longest times to achieve stabilization. During the initial sampling, the purging time should be extended beyond what initially appears to be stabilization as a check to ensure that the parameter stability is maintained.

**iii) Low Flow Purging**

Another purge method using the stabilization of indicator parameters is low-flow (minimal drawdown) well purging. This technique is based upon placing the pump intake at the screened interval, or in the case of fractured rock, the water-bearing zone of interest. The well is pumped at a very low rate, commonly less than 0.5 liters per minute, while producing less than 0.1 meters of drawdown. Pumping continues until various indicator parameters stabilize. The objective is to produce minimal drawdown and less stress upon the aquifer while obtaining a sample from the aquifer interval of interest. Lack of definitive well construction or water-producing interval information negates the use of this purge method.

Low-flow purging often creates much less purge water. Some purge water contains various substances which cannot be disposed of on the ground necessitating disposal. In these cases, low-flow purging can greatly reduce the costs of disposal. In addition, purge time is often substantially less. Set-up is usually more complex, and costs may therefore be higher than when using other purge methods.

Indicator parameters typically include temperature, pH, redox potential, conductivity, dissolved oxygen (DO), and turbidity. These common stabilization parameters are often used to indicate that the water coming from the pumped interval is aquifer water. Although often not very sensitive to changes between borehole and aquifer water, temperature and pH are usually included because they are easy to measure, and the data is commonly used for other field analysis reasons. The minimum number of parameters to measure should include pH, conductivity, and dissolved oxygen. Stabilization is indicated after three successive readings taken at 3- to 5-minute intervals. Indicator parameters should show a change of less than ± 0.1 for pH, ± 3% for conductivity, ± 10% mv for redox potential, and ± 10% for turbidity and dissolved oxygen. The stabilization rates put forth are a guideline. Experience may dictate the need for more or less tolerance in particular wells or situations.

If a well has a history of water quality data produced using a different well purging method, the result should be compared with the new low-flow purge results. Significant variation in data will require justification of continued use of the low-flow purge method. Depending upon the situation, purge methods may need to return to the original method.

**iv) Special Problems of Low-Yielding Wells**

Low-yield wells present a special problem for the sampler in that they may take hours, or even days, to recover after purging so that there is enough water to sample. This waiting period not only increases the cost of sampling, but also allows changes in water quality to occur between the time the sample water enters the casing and the time it is collected. This is especially problematic when sampling volatile constituents.

In practice, very low-yield wells are commonly pumped dry and sampled the following day if necessary. This practice is believed to result in water being sampled that is not representative of the aquifer being sampled from the well due to the loss of volatiles and oxygenation of the water during the waiting period. This results from pumping the well dry and exposing the formation to the atmosphere. While there does not appear to be any method uniformly agreed upon to eliminate these concerns, the following considerations are suggested:

- Purge in such a way that the water level does not fall below the well screen.

- Evaluate the use of larger diameter wells that may deliver the required amount of sample water more quickly than small diameter wells.

- If full recovery cannot be achieved within two hours, collect the required amount of water as it becomes available, collecting samples for parameters in order of decreasing volatility.

**v) No-Purge Methods**

Passive samplers offer an alternative to traditional purge methods. Commonly used technologies include polyethylene (or passive) diffusion bags (PDBs) and HydraSleeves™. Some sampler types operate through diffusion of contaminants into the device; others collect a discrete grab sample. A key advantage of passive samplers is that no purge water is generated that requires treatment or disposal. Other advantages include reduction of field sampling time and potentially less variability in sample results. It should be noted that passive sampling methods that detect only the presence or absence of contaminants may be utilized for characterization, but are not recommended for attainment sampling. Additionally, if the screening investigation indicates that regulated substances are present, and if the aquifer recharge rate is reasonable, conventional grab sampling should be performed to obtain quantitative data on contaminant concentrations as part of a complete characterization effort.

Some important limitations should be evaluated when considering the use of passive samplers. The well construction, hydraulic properties of the aquifer, and contaminant type and distribution should be known and discussed with DEP prior to engaging in a full-scale sampling program (see the references for further information).

- No-purge sampling methods rely on adequate groundwater flow through the well screen. If the seepage velocity is low or the screen is fouled, then the exchange rate of water in the well could be slow, the water may be stagnant, and the sample may not be representative of groundwater in the formation.

- Some devices are incompatible with certain analytes. For example, most VOCs readily diffuse through polyethylene, but some (such as MTBE) do not. Polyethylene diffusion bags cannot be used to sample semi-volatile organic compounds (SVOCs) or inorganics.

- Because passive samplers collect from a discrete interval, results may be sensitive to the depth at which the device is placed. If flow is stratified in the formation or localized at bedrock fractures, or if the contaminant is density-stratified in the water column, then deployment depth is important. Some sampler types allow multiple devices to be arrayed vertically on a tether, allowing the remediator to better determine an optimal depth.

Passive samplers will not necessarily produce results equivalent to purge methods. Ideally, a consistent purge and sampling methodology will be used for all wells in the site network from the beginning of characterization until the end of attainment. If a change in the sampling method is being proposed midway through a monitoring program, then sufficient side-by-side testing with the current approach should be performed and discussed with DEP to determine if the change in method is appropriate.

**vi) Summary on Purging**

The following general statements can be made with respect to purging:

- Every groundwater monitoring plan should contain a section discussing how wells will be purged.

- It is often desirable to use the same device for sampling that was used for purging. In this case the purge pump can be set within the screened section of the well or across from the yielding zone being monitored.

- If different devices are used for purging and sampling, purging should begin at the static water surface and the device should be lowered down the well at a rate proportional to water stored in the well bore. Because of the better mixing of water in wells with multiple yielding zones, this technique is considered preferable for sampling wells with multiple yielding zones where a composite sample of water in the yielding zones is desired (see Section C.5 on Well Depths, Screen Lengths, and Open Intervals).

- Where the same device is used to sample and purge a well, it should be established that the sampling device will not change the quality of the groundwater it contacts.

- In sampling for some analytes, such as volatile organics, it is critical that the discharge be reduced to approximately 100 ml/minute to minimize degassing and aeration (Barcelona et al., 1984). Flow control should be achieved by means of an electric current using a rheostat rather than by valving or other flow restrictors.

- Purging should be completed without lowering the water level in the well below the well screen or water-bearing zone being sampled.

Never purge a well at a rate or in a way that causes water to cascade into the well bore, resulting in increased degassing and volatilization.

**e) Management of Purge Water**

The first step in the management of monitoring well purge water is to minimize its generation. Consideration should be given to techniques that minimize the amount of purge water produced, such as low-flow or low-volume purging, or a no-purge method. Purge water should be handled in a way that is environmentally compatible with the volume generated, the type and concentration of confirmed or suspected contaminants, and the specific site conditions. A procedure that can be used is outlined in Table A-2. The procedure is designed to ensure that potentially contaminated purge water is disposed properly without contaminating other environmental media.

The following items should be considered when handling purge water:

- Purge water should be containerized until it is characterized by laboratory analysis. Containers with purge water comingled from multiple wells should use the highest concentration seen in any one of the wells from which the comingled purge water was produced, unless the comingled purge water is sampled.

- Purge water that has been characterized with no detections (i.e., with analytical results less than method detection limits (MDLs)) may be handled as uncontaminated groundwater under Table A-2.

- Purge water that has been characterized with detections of constituents that do not exceed the Act 2 Residential, Used Aquifer Groundwater MSCs may utilize any of the actions described in the contaminated groundwater section of Table A-2. Discharging to the ground surface to return water to the impacted groundwater plume (re-infiltration) under action (d) is an option if it does not create runoff. Discharge to a surface water, wetland, storm drain or paved surface that drains to a channel or stormwater conveyance requires a permit or other appropriate regulatory authorization.

- Purge water that has been characterized with detections of constituents that exceed the residential used aquifer MSCs should be managed as contaminated groundwater utilizing one of the actions described in (a), (b), (d), or (e) of Table A-2. If action (e) is utilized, one of the approved methods is as follows (for organic constituents only):

  – Place up to 20 gallons/well of contaminated purge water onto the ground surface of the site in a controlled manner for re-infiltration after treatment with portable engineered carbon adsorption units designed and operated to remove the organic contaminants to levels below residential used aquifer MSCs according to the following:

- Re-infiltration may only occur within the area of groundwater contamination exceeding Act 2 residential, used aquifer MSCs;

- Placement on site should not create runoff that will enter surface water, wetlands, storm drains or other water conveyances to surface water;

- All contaminants should be capable of being treated by carbon adsorption;

- Carbon adsorption units should be designed to provide contact time for the amount of carbon at the expected levels of raw water contamination to reach residential used aquifer MSCs;

- A sample should be collected to demonstrate the unit has functioned as intended. Samples should be collected at the beginning and end of the filtration cycle; and

- Purge water should contain no free product.

**f) Private Wells**

If a well is a private water supply, sample as close to the well as physically practical and prior to any treatment or filtering devices if possible and practical. If sample collection must be from a holding tank, allow water to flow long enough to flush the tank and the lines; when the pump in the well is triggered and turned on, verification of tank flushing is provided. If a sample that passes through a treatment tank must be taken, the type, size, and purpose of the unit should be noted on the sample data sheet and in the field log book.

**g) Filtering**

When possible, avoid collecting samples which are turbid, colored, cloudy or contain significant suspended matter. Exceptions to this include when the sample site has been pumped and flushed or has been naturally flowing for a sufficient time to confirm that these conditions are representative of the aquifer conditions.

Unless analysis of unfiltered samples for “total metals” is specifically required by program regulation or guidance, all samples for metals analysis should be field-filtered through a 0.45-micron filter prior to analysis. Filtering samples for SVOC analysis is not appropriate to be conducted in the field as SVOCs have been known to adhere to certain materials used during the filtration process.

**Table A-2: Procedure for the Management of Well Purge Water from Groundwater Sampling**

<table>
<tr><th>TYPE OF GROUNDWATER</th><th>ACTION</th></tr>
<tr><td>Purge Water – Shown to not exceed the Act 2 residential, used aquifer groundwater standards contained in Tables A-1 and A-2 of 25 Pa. Code Chapter 250.</td><td>Purge water may be placed on the ground surface (onsite) provided precautions are in place to avoid erosion or runoff. Discharge to a surface water, wetland, storm drain or paved surface is prohibited without a permit or other appropriate regulatory authorization.</td></tr>
<tr><td>Purge Water – Shown to exceed the Act 2 residential, used aquifer groundwater standards contained in Tables A-1 and A-2 of 25 Pa. Code Chapter 250.</td><td>Management of purge water may proceed with one of the following options:<br><br>a) Convey directly into an on-site treatment plant or leachate collection system for final treatment.<br><br>b) Transport to off-site treatment facility.<br><br>c) Place in a temporary storage unit onsite for analysis to determine the final disposition.<br><br>d) De minimis quantities may be treated and placed on the ground surface onsite provided the type and concentration of contamination(s) will not adversely impact surface water or wetlands, or further contaminate soil or groundwater. The treatment unit must be rated to remove the identified contaminants and must be operated and maintained to ensure contaminant removal to Act 2 residential used aquifer standards.<br><br>e) Other methods approved by DEP (may require a permit for specific site conditions).</td></tr>
<tr><td>Purge Water where water quality is not determined</td><td>Purge water that is not characterized needs to be containerized until laboratory analysis is complete. Containers with purge water comingled from multiple wells should use the highest concentration seen in any one of the wells from which the comingled purge water was produced, unless the comingled purge water is sampled. Following analysis of purge water, it may be treated as one of the two categories above.</td></tr>
</table>

**h) Sample Preservation**

Perform sample preservation techniques onsite as soon as possible after the sample is collected. Complete preservation of samples is a practical impossibility. Regardless of the nature of the sample, complete stability for every constituent can never be achieved. For this reason, samples should be analyzed as soon as possible. However, chemical and biological changes occurring in the sample may be slowed significantly by proper preservation techniques.

Chemical changes generally happen because of a shift in the physical conditions of the sample. Under a fluctuation in reducing or oxidizing conditions, the valence number of the cations or anions may change; other analytes may volatilize or dissolve; metal cations may form complexes or precipitate as hydroxides, or they may adsorb onto surfaces.

Biological changes can also alter the valence of a constituent. Organic processes may bind soluble material into the cell structure, or cell material may be released into solution.

Methods of preservation are relatively limited and are generally intended to: 1) retard biological activity, 2) retard hydrolysis of chemical compounds and complexes, 3) reduce the volatility of constituents, and 4) reduce sorption effects. Preservation methods are generally limited to pH control, chemical addition, refrigeration, freezing, and selecting the type of material used to contain the sample.

The best overall preservation technique is refrigeration at, or about, 4°C. Refrigeration primarily helps to inhibit bacteria. However, this method is not always applicable to all types of samples.

Acids such as $HNO_3$ and $H_2SO_4$ can be used to prevent precipitation and inhibit the growth of bacteria. Preservation methods for any specific analysis should be discussed with the accredited laboratory that is analyzing the samples.

**i) Decontamination of Sampling Devices**

All non-disposable and non-dedicated equipment that is submerged in a monitoring well or contacts groundwater will need to be cleaned between sampling additional wells to prevent cross-contamination. Generally, the level of decontamination is dependent on the level and type of suspected or known contaminants. Extreme care should be taken to avoid any decontamination product from being introduced into a groundwater sample.

The decontamination area should be established upwind of sampling activities and implemented on a layer of polyethylene sheeting to prevent surface soils from contacting the equipment. The following steps summarize recommended decontamination procedures for an Act 2 site:

- Wash with non-phosphate detergent and potable water. Use bristle brush made from inert material to help remove visible soil;
- Rinse with potable water - pressure spray is recommended;
- If collecting samples for metals analysis, rinsing with 10% hydrochloric or nitric acid;

- Rinse liberally with deionized/distilled water –pressure spray is recommended;
- If collecting samples for organics analysis, rinsing with solvent-grade isopropanol, acetone, or methanol (should not be a solvent of potential interest to the investigation);
- Rinse liberally with deionized/distilled water – pressure spray is recommended;
- Air-dry;
- Wrap with inert material (such as aluminum foil) if equipment is not being used promptly.

**j) Field Sampling Logbook**

A field logbook or field sampling forms should be completed and maintained for all sampling events. The following list provides some examples of pertinent information that should be documented:

- date/time of sample collection for each well
- well identification
- well depth
- presence of immiscible layers and detection method (i.e., an interface probe)
- thickness of immiscible layers, if applicable
- estimated well yield (high, moderate, or low)
- purging device, purge volume, and pumping rate
- duration of well purging
- measured field parameters (see 4.3.3)
- sample appearance
- description on any abnormalities around the wellhead (standing/ponded water, evidence of vandalization, etc.)
- description of any wellhead materials that were or need to be replaced (sanitary well cap, well lid or well lid bolts, locking devices, etc.)

### k) Chain-of-Custody

A chain-of-custody record provides a legal document that traces sample procession from time of collection to final laboratory analysis. The document should account for all samples collected that require laboratory analyses and provide the following information:

- sample identification number
- printed name and signature of sample collector(s)
- date/time of collection for each sample
- sample media type (i.e., groundwater)
- thickness of immiscible layers, if applicable
- well identification
- type and number of containers for each sample
- laboratory parameters requested for analyses
- type(s) of preservatives used
- carrier used, if applicable
- printed name and signature of person(s) involved in the chain of possession
- date/time samples were relinquished by the sampler and received by the laboratory
- presence/absence of ice in cooler or other sample holding device
- special handling instructions for the laboratory, if applicable

## 4. References

Barcelona, M.J., Helfrich, J.A., Garske, E.E., and Gibb, J.P., 1984, A Laboratory Evaluation of Groundwater Sampling Mechanisms, Groundwater Monitoring Review, v.4, No.2, pp. 32-41.

Driscoll, F.G., 1986, Groundwater and Wells, Second Edition, Johnson Filtration Systems, Inc., St. Paul, Minnesota 55112, 1089 pp.

Gibb, J.P., Schuller, R.M., and Griffin, R.A., 1981, Procedures for the Collection of Representative Water Quality Data from Monitoring Wells, Cooperative Groundwater Report 7, Illinois State Water Survey and Illinois State Geological Survey, Champaign, IL.

Herzog, B., J. Pennino, and G. Nielsen, 1991, Ground-water sampling. In: Practical Handbook of Ground-Water Monitoring. D. M. Nielsen, ed. Lewis Publishers. Chelsea, Michigan. pp. 449-499

Interstate Technology Regulatory Council, 2004, Technical and Regulatory Guidance for Using Polyethylene Diffusion Bag Samplers to Monitor Volatile Organic Compounds in Groundwater.

Interstate Technology Regulatory Council, 2006, Technology Overview of Passive Sampler Technologies.

Interstate Technology Regulatory Council, 2007, Protocol for Use of Five Passive Samplers to Sample for a Variety of Contaminants in Groundwater, 121 pp.

Nielsen, D.M., (Editor), 1991, Practical Handbook of Ground-Water Monitoring, NWWA, Lewis Publishers, Inc., Chelsea, Michigan 48118, 717 pp.

Nielsen, D.M., Nielsen, G., 2007, The Essential Handbook of Groundwater Sampling, CRC Press.

Ohio Environmental Protection Agency, 2012, Technical Guidance Manual for Groundwater Investigations, Chapter 10, Groundwater Sampling.

U.S. Environmental Protection Agency, 2010, Low Stress (Low Flow) Purging and Sampling Procedure for the Collection of Groundwater Samples from Monitoring Wells, 30 pp.

U.S. Geological Survey, 2001, User’s Guide for Polyethylene-Based Passive Diffusion Bag Samplers to Obtain Volatile Organic Compound Concentrations in Wells, Water-Resources Investigations Report 01-4060.

U.S. Geological Survey, 2006, Collection of water samples (ver. 2.0): U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A4, September 2006.

## E. Well Decommission Procedures

### 1. Introduction

Unsealed or improperly sealed wells may threaten public health and safety and the quality of the groundwater resources. Therefore, the proper abandonment (decommissioning) of a well is a critical final step in its service life.

Act 610, the Water Well Drillers License Act (32 P.S. § 645.1, et seq), includes a provision for abandonment of wells. This legislation makes it the responsibility of a well owner to properly seal an abandoned well in accordance with the rules and regulations of DCNR. In the absence of more stringent regulatory standards, the procedures outlined in this section represent minimum guidelines for proper decommissioning of wells and borings. These procedures may be applicable for, but not limited to, public and domestic water supply wells, monitoring wells, borings or drive points drilled to collect subsurface information, test borings for groundwater exploration, and dry wells (drains or borings to the subsurface).

Proper well decommissioning accomplishes the following: 1) eliminates the physical hazard of the well (the hole in the ground and the wellhead protruding above surface grade when applicable); 2) eliminates a pathway for the introduction and migration of contamination; and 3) prevents hydrologic changes in the aquifer system, such as the changes in hydraulic head and the mixing of water between aquifers. The proper decommissioning method will depend on both the reason for abandonment and the condition and construction details of the boring or well and the specific threat of existing and potential contamination sources near the well bore.

An unused and decommissioned well could be the conduit for spread of contamination. The lack of well decommissioning and a poorly sealed well could both result in the spread of contamination into previously uncontaminated areas for which the well owner or contractor may be responsible.

### 2. Well Characterization

Effective decommissioning depends on knowledge of the well construction, site geology, and hydrogeology. The importance of a full characterization increases as the complexity of the well construction, site geology, and the risk of aquifer contamination increases. Construction information for wells drilled since 1966 may be available from the DCNR BTGS PaGWIS database. Additional well construction data and information describing the hydrologic characteristics of geologic formations may be available from reports published by BTGS and the USGS. Site or program records also may exist. The well should be positively identified before initiating the decommissioning. Field information should be compared with any existing information.

Water levels and well depths can be measured with a well sounder, weighted tape measure, or downhole camera. In critical situations, well construction details and hydrogeology can be determined with borehole geophysics or a downhole camera. For example, a caliper log, which is used to determine the borehole diameter, can be very helpful in locating cavernous areas in open hole wells.

## 3. Well Preparation

If possible, the borehole should be cleared of obstructions prior to decommissioning. Obstructions such as pumps, pipes, wiring, and air lines must be pulled. Well preparation also may involve "fishing" obstacles out of the borehole. An attempt should be made to pull the casing when it will not jeopardize the integrity of the borehole. Before the casing is pulled, the well should be grouted to near the bottom of the casing. This will at least provide some seal if the well collapses after the casing is pulled.

The presence of nested or telescoped casing strings complicates well decommissioning. Inner strings should be removed when possible, but only when removal will not jeopardize the decommissioning of the well. If inner strings cannot be removed and sealing of the annular space is required, then the inner string should be vertically split (plastic-cased wells) or cut (metal-cased wells) at intervals necessary to ensure complete filling of the annular space.

Damaged, poorly constructed or dilapidated wells may need to be re-drilled prior to application of proper decommissioning techniques. Also, in situations where intermixing of aquifers is likely, the borehole may need to be re-drilled.

## 4. Materials and Methods

### a) Aggregate

Materials that eliminate the physical hazard and open space of the borehole, but do not prevent the flow of water through the well bore, are categorized as aggregate. Aggregates consist of sand, crushed stone or similar material that is used to fill the well. Aggregates should be uncontaminated and of consistent size to minimize bridging during placement.

Aggregate is usually not placed in wells smaller than two inches in diameter. Nominal size of the aggregate should be no more than 1/4 of the minimum well diameter through which it must pass during placement. Because aggregate is usually poured from the top of the well, care should be taken to prevent bridging by slowly pouring the aggregate and monitoring the progress with frequent depth measurements. The volume of aggregate needed should be calculated prior to placement into the well.

Aggregates may be used in the following circumstances: 1) there is no need to penetrate or seal fractures, joints or other openings in the interval to be filled; 2) a watertight seal is not required in the interval to be filled; 3) the hole is caving; 4) the interval does not penetrate a perched or confined aquifer; and 5) the interval does not penetrate more than one aquifer. If aggregate is used, a casing seal should be installed (see Section E.5.a). The use of aggregate and a casing seal should be consistent with the future land use.

## b) Sealants

Sealants are used in well decommissioning to provide a watertight barrier and prevent the migration of water in the well bore, in the annular spaces or in fractures and openings adjacent to the well bore. Sealants usually consist of Portland cement-based grouts, "bentonite" clay, or combinations of these substances. Additives are frequently used to enhance or delay specific properties such as viscosity, setting time, shrinkage, or strength.

Sealing mixtures should be formulated to minimize shrinkage and ensure compatibility with the chemistry of the groundwater in the well.

To avoid the bridging of sealants in the well, sealing should be performed under pressure from the bottom upward. A grout pump and tremie pipe are preferred for delivering grout to the bottom of the well. This method ensures the positive displacement of the water in the well and will minimize dilution or separation of the grout.

If aggregate is to be placed above sealant, sufficient curing time should be allotted before placing the aggregate above the seal. Curing time for grout using Type 1 cement is typically 24-48 hours, and 12 hours for Type III cement.

General types of sealants are defined as follows:

<u>Neat cement grout:</u> Neat cement grout is generally formulated using a ratio of one 94-pound bag of Portland cement to no more than 6 gallons of water. This grout is superior for sealing small openings, for penetrating any annular space outside of the casings, and for filling voids in the surrounding rocks. When applied under pressure, neat cement grout is strongly favored for sealing artesian wells or those penetrating more than one aquifer. Neat cement grout is generally preferred to concrete grout because it avoids the problem of separation of the aggregate and the cement. Neat cement grout can be susceptible to shrinkage, and the heat of hydration can possibly damage some plastic casing materials.

<u>Concrete grout:</u> Concrete grout consists of a ratio of not more than six gallons of water, one 94-pound bag of Portland cement, and an equal volume of sand. This grout is generally used for filling the upper part of the well above the water-bearing zone, for plugging short sections of casings, or for filling large-diameter wells.

Concrete grout, which makes a stronger seal than neat cement, may not significantly penetrate seams, crevices or interstices. Grout pumps can handle sand without being immediately damaged. Aggregate particles bigger than this may damage the pump. If not properly emplaced, the aggregate is apt to separate from the cement. Concrete grout should generally not be placed below the water level in a well, unless a tremie pipe and a grout pump are used.

<u>Grout additives:</u> Some bentonite (2 to 8 percent) can be added to neat cement or concrete grout to decrease the amount of shrinkage. Other additives can be used

to alter the curing time or the permeability of the grout. For example, calcium chloride can be used as a curing accelerator.

High-solids sodium bentonite: This type of grout is composed of 15-20 percent solids content by weight of sodium bentonite when mixed with water. To determine the percentage content, the weight of bentonite is divided by the weight of the water plus the weight of the bentonite. For example, if 75 pounds of powdered bentonite and 250 pounds of granular bentonite were mixed in 150 gallons of water (at 8.34 pounds per gallon), the percentage of high-solids bentonite is approximately 20 percent [325/(1251+325)]. High-solids bentonite must be pumped before its viscosity is lowered. Pumping pressures higher than those used for cement grouts are usually necessary. Hydration of the bentonite must be delayed until it has been placed down the well. This can be done by: 1) using additives with the dry bentonite or in the water; 2) mixing calcium bentonite (it expands less) with sodium bentonite; or 3) using granular bentonite, which has less surface area.

In addition, positive displacement pumps such as piston, gear, and moyno (progressive cavity) pumps should be used because pumps that shear the grout (such as centrifugal pumps) will accelerate congealing of the bentonite. A paddle mixer is typically used to mix the grout. A high-solids bentonite grout is not made from bentonite that is labeled as drilling fluid or gel.

#### c) Bridge Seals

A bridge seal can be used to isolate cavernous sections of a well, to isolate two producing zones in the well, or to provide the structural integrity necessary to support overlying materials, and thus protect underlying aggregate or sealants from excessive compressive force. Bridge seals are usually constructed by installing an expandable plug made of wood, neoprene, or a pneumatic or other mechanical packer. Additional aggregate can be placed above the bridge.

### 5. Recommendations

The complexity of the decommissioning procedure depends primarily on the site hydrogeology, geology, well construction, and the groundwater quality. Four principal complicating factors have been identified, which include: 1) artesian conditions, 2) multiple aquifers, 3) cavernous rocks, and 4) the threat or presence of contamination. The recommended procedures for abandoning wells will be more rigorous with the presence of one or more complicating factors. The procedures may vary from a simple casing seal above aggregate to entirely grouting a well using a tremie pipe after existing casing has been ripped or perforated. Figure A-8 summarizes the general approach to well decommissioning.

#### a) Casing Seal

The transition from well casing to open borehole is the most suspect zone for migration of water. To minimize the movement of water (contaminated or otherwise) from the overlying, less consolidated materials to the lower water-bearing units, this zone should be sealed. Generally, this can be accomplished by filling at least the upper 10 feet of open borehole and the lower five feet of casing with sealant. The length of open borehole sealed should be increased if extenuating circumstances exist. Such circumstances would include a history of bacterial contamination, saprolitic bedrock, or possibly deep fracture zones. Water-bearing zones reported in the upper 20 feet or so of open borehole are indications of fractures and warrant the use of additional sealant. Casing that is deteriorated should be sealed along its entire length. If the casing is to be pulled, the sealant used should remain fluid for an adequate time to permit removal of the casing.

If the casing is to remain, then whenever feasible, it should be cut off below land surface. After the casing seal discussed above achieves adequate strength, the open casing should, at a minimum, be filled with aggregate. It is strongly suggested that a sealant be used in the upper two to five feet of casing.

**b) Wells in Unconfined or Semi-Confined Conditions**

These are the most common well types in Pennsylvania. The geology may consist of either unconsolidated or consolidated materials. When applicable, unconfined wells in non-contaminated areas may be satisfactorily decommissioned using aggregate materials up to 10-15 feet below the ground surface. Monitoring wells located at sites with no known contamination might be decommissioned in this manner. The casing seal should be installed above the aggregate. A sealant may be used over the entire depth.

**c) Wells at Contaminated Sites**

A decommissioned, contaminated well often mixes contaminated groundwater with uncontaminated groundwater. Complete and uniform sealing of the well from the bottom to the surface is required. Therefore, proper well preparation (Section E.3) should be accomplished before the well is sealed with a proper sealant (Section E.4.b).

**d) Flowing Wells**

The sealing of artesian wells requires special attention. The flow of groundwater may be sufficient to make sealing by gravity placement of concrete, cement grout, neat cement, clay or sand impractical. In such wells, large stone aggregate (not more than 1/4 of the diameter of the hole), or well packers (pneumatic or other) will be needed to restrict the flow and thereby permit the gravity placement of sealing material above the zone where water is produced. If plugs are used, they should be several times longer than the diameter of the well to prevent tilting. Seals should be designed to withstand the maximum anticipated hydraulic head of the artesian aquifer.

Because it is very important in wells of this type to prevent circulation between water yielding zones, or loss of water to the surface or annular spacing outside of the casing, it is recommended to pressure grout the well with cement using the minimum volume of water during mixing that will permit handling.

For wells in which the hydrostatic head producing flow to the surface is low, the movement of water may be stopped by extending the well casing to an elevation above the artesian pressure surface.

**e) Wells with Complicating Factors at Contaminated Sites**

Wells with one or more of the above complicating factors that are to be decommissioned in areas with contaminated groundwater, or in areas where the groundwater is at a high risk for future contamination, require the most rigorous decommissioning procedures. In general, the entire length of these wells should be sealed.

When the threat of contamination has been established, the elimination of a potential flowpath is critical. For example, a contaminated well in a karst terrane must be carefully sealed to avoid exacerbating the situation. In general, the entire lengths of these wells should be sealed. In some situations, a bridge seal may need to be installed, and casing may have to be perforated. In each case, a prudent method should be selected which will eliminate all potential vertical flowpaths.

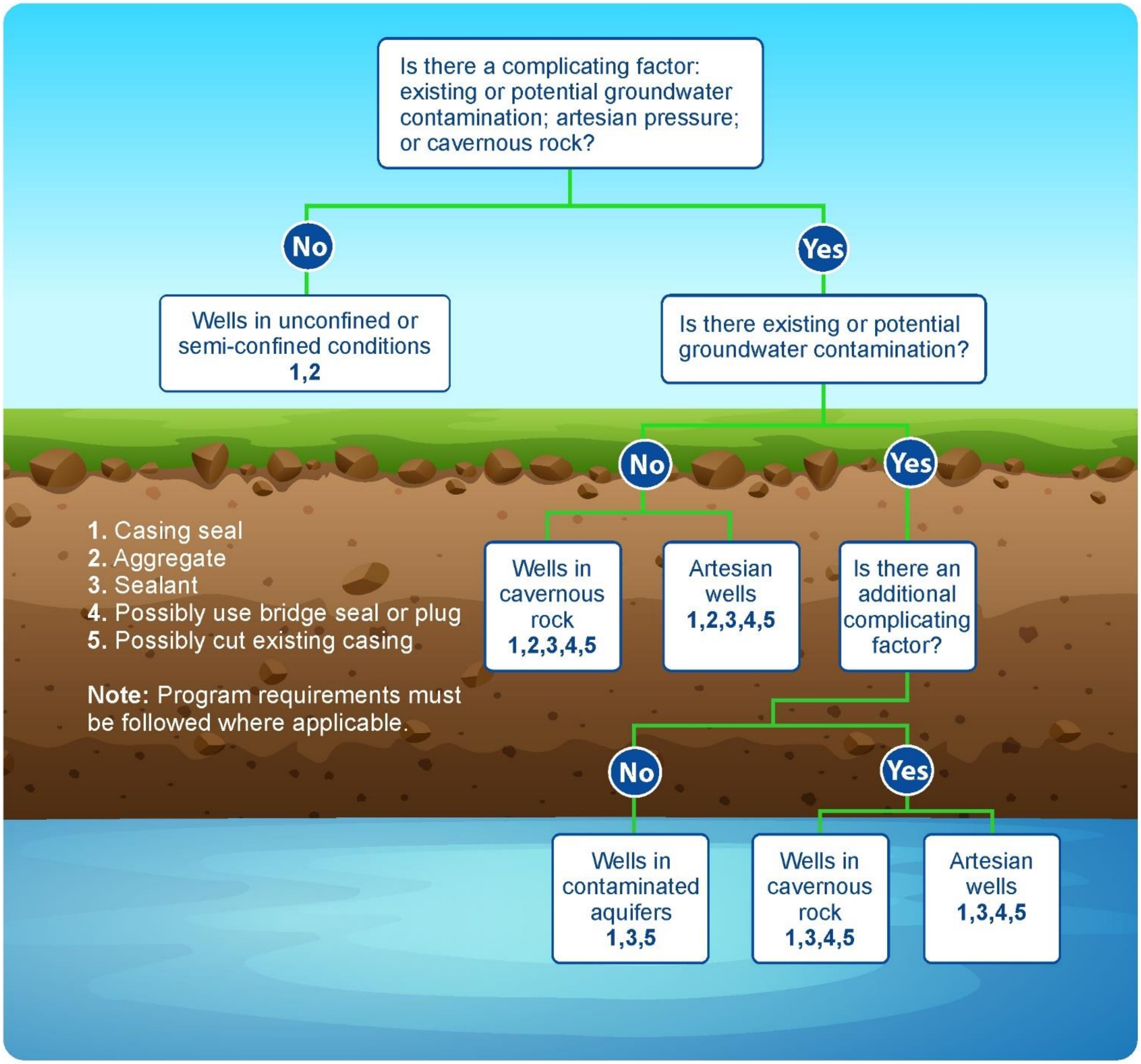
**f) Monitoring Wells**

Monitoring wells which are installed for an investigation, cleanup or other monitoring in a program that has no rules or regulations for decommissioning, such as the Act 2 program, should be decommissioned in accordance with the following guidelines.

Monitoring wells that were installed and continue to function as designed can usually be decommissioned in place after they are no longer needed. Exceptions would include wells whose design precludes complete and effective placement of sealant and wells in locations subject to future disturbance that could compromise the decommissioning. In such instances, all tubing, screens, casings, aggregate, backfilling, and sealant should be cleaned from the boring and the hole should be completely filled with an appropriate sealant.

Monitoring wells that are abandoned in place should be completely filled with sealant. Screened intervals can be backfilled with inert aggregate if sealant may alter the groundwater chemistry, thereby jeopardizing ongoing monitoring at the facility. Intervals between screens, and between the last screen and the surface, must be filled with sealant. Generally, sealant should be emplaced from the bottom of the interval being sealed to the top of that interval. Protective casings, riser pipes, tubing, and other appurtenances at the surface which could not be removed should be cut off below grade after the sealant has properly set. When decommissioning will be completed below the finished grade, the area of the boring should be covered with a layer of bentonite, grout, concrete, or other sealant before backfilling to grade.

**Figure A-8: Summary of Procedures for Well Decommissioning**




**Note:** Figure must be used in conjunction with the text. Reference Section A.E.

## 6. Existing Regulations and Standards

17 Pa. Code § 47.8 requires that the owner or consultant who is to abandon the well notify DCNR's BTGS of the intent to decommission a well at least 10 days before the well is sealed or filled.

## 7. Reporting

All decommissioned wells shall be reported to BTGS, along with any bureau that requires a report, on forms required by BTGS (and any other pertinent forms). If available, the original driller's log should be included, along with the details of the well decommissioning procedure. A photograph should be taken of the site, and a reference map should be made, showing the location of the decommissioned well. It also may be appropriate to survey the exact location of the well (if not already completed). Licensed drillers may use the online application WebDriller to complete the well decommissioning report.

## 8. References


American Water Works Association, 1990, Abandonment of Test Holes, partially completed wells and completed wells: AWWA Standard for Water Wells, pp. 25-26.

Driscoll, F.G., 1986, Groundwater and Wells, 2nd ed., Johnson Filtration Systems, Inc., St. Paul, Minnesota 55112, 1089 pp.

Nye, J.D., September 1987, Abandoned Wells - How One State Deals with Them, Water Well Journal, pp. 41-46

Renz, M.E., May 1989, In Situ Decommissioning of Ground Water Monitoring Wells, Water Well Journal, pp. 58-60.

U.S. Environmental Protection Agency, 1975, Manual of Water Well Construction Practices, Office of Water Supply, EPA-570/9-75-001.

## F. Quality Assurance/Quality Control Requirements

### 1. Purpose

A Quality Assurance/Quality Control Plan (QA/QC Plan) is a detailed account of methods and procedures used for data collection (i.e., monitoring) activities. This plan, when properly developed and implemented, ensures that adequate control and documentation procedures are utilized, from initiation to completion of the monitoring, so that the data generated is of the highest quality and can be used for the intended purpose with confidence. A QA/QC plan is also an effective tool in assessing and assuring the completeness and adequacy of the basic monitoring plan.

### 2. Design

A QA/QC plan should be designed to satisfy the objectives of the monitoring project. Although the elements of each QA/QC plan described below will be similar, the intended uses of the collected data will determine the requirements associated with the monitoring activity. In most cases, there will be sufficient differences within monitoring activities for each project to require a specific QA/QC plan.

The following paragraphs describe the basic elements of a QA/QC plan. In most cases, the proper development and adherence to this format will be sufficient to ensure that the data collection meets the objectives of a project. However, in some cases it may be necessary to include additional considerations that may be unique to a specific site and/or project.

### 3. Elements

- Project Name or Title: Provide the project identification and location.

- Project Required by: Provide the reason(s) or requirement(s) for the project.

- Date of Requirement: Provide date the project was required, either by legal or other order.

- Date of Project Initiation: Provide date that the project was implemented.

- Project Officer(s): Provide name(s) of individual(s) responsible for managing or overseeing the project.

- Quality Assurance Officer(s): Provide name(s) of individual(s) responsible for development of and adherence to the QA/QC plan.

- Project Description: Provide the following: 1) an objective and scope statement which comprehensively describes the specific objectives and goals of the project, such as determining treatment technology effectiveness, or remediation effectiveness for specific parameters; 2) a data usage statement that details how the monitoring data will be evaluated, including any statistical or other methods; 3) a description of the location of monitoring stations and reasons for the locations, including geologic, hydrogeologic or other considerations; and 4) a description of the monitoring analytes and frequency of sample collection, including the expected number of samples to be collected for each analyte, the sample matrix (i.e., water), the exact analytical method, reasons for selection of analytes, and sample preservation method(s) and holding time(s).

- Project Organization and Responsibility: Provide a list of key personnel and their corresponding responsibilities, including the position and/or individual in charge of the following functions: field sampling operations, field sampling QA/QC, laboratory analyses, laboratory analyses QA/QC, data processing activities, data processing QA/QC and overall project coordination.

- Project Fiscal Information: Provide an estimate in work days of the project time needed for data collection, laboratory support, data input, quality assurance and report preparation in work days.

- Schedule of Tasks and Products: Provide a projected schedule for completing the various tasks and developing the products associated with the project, such as sample collections (monthly, quarterly, etc.), data analysis/reports (quarterly, annual, biennial, etc.).

- Data Quality Requirements and Assessments: Provide a description of data accuracy and precision, data representativeness, data comparability, and data completeness.

- Sampling Procedures: Provide a description of the procedures and equipment/hardware used to collect samples from monitoring wells or other sites, including sampling containers and field preservation and transport procedures.

- Sampling Plan: A sampling plan should provide necessary guidance for the number and types of sampling QCs to be used. The following is a list of common sample QC types and the recommended minimum frequency if used. It is important to remember that all QC samples should be treated with the same dechlorination and/or preserving reagents as the associated field samples.

    – Trip Blanks - These are appropriate sample containers filled with laboratory-quality reagent water that are transported to and from the sampling site(s) and shipped with the samples to the laboratory for analysis. The intent of these samples is to determine whether cross contamination occurred during the shipping process. They are also used to validate that the sampling containers were clean. Each sampling event that uses this type of QC should have a minimum of one trip blank for each container type used.

    – Field Blanks - These are appropriate sample containers that are filled with laboratory-quality reagent water at the sampling site(s) and shipped with the samples to the laboratory for analysis. These samples are intended to determine if cross-contamination occurred during the sampling process due to ambient conditions. They are also used to validate that the sampling containers were clean. Each sampling event that uses this type of QC should have a minimum of one field blank for each sampling site and of each container type used. This type of sampling QC is most useful when sampling for VOC's.

– Rinsate Blanks - These are samples of laboratory-quality reagent water used to rinse the collection device, including filtration devices and filters, which contact the same surfaces as the sample. The QC samples(s) are then submitted with the field samples for analysis. This type of QC sample helps to determine if the sample collection device is contributing any detectable material to the sample. The minimum number of blanks needed, if this type of QC is utilized, is dependent upon operational considerations. A minimum of two rinsate blanks should be submitted (one before sampling and one after sampling) if multiple samples are being collected with the same decontaminated collection device. If you are using disposable sample collection devices or multiple pre-cleaned devices, then a single representative sample should suffice.

– Split/Duplicate Samples - This is a single, large sample that has been homogenized, split into two or more individual samples, with each sample submitted independently for analysis. This QC determines the amount of variance in the entire sampling/analysis process. This type of QC is not recommended for samples analyzed for analytes that would be adversely affected by the homogenization process (i.e. VOC's). The minimum number of this type of sampling QC, if utilized, is one per sampling event, with a rate of 5 percent to 10 percent commonly used.

– Replicate Samples - Comprised of two or more samples collected from the same source, in a very short time frame (i.e., minutes), with each sample submitted independently for analysis. This QC measure, like the split/duplicate sample, determines the amount of variance in the entire sampling/analysis process. The amount of variance determined by this type of QC may be larger than that of a split/duplicate sample. The use of this type of QC also presumes that the sample's materials are already homogenous. This type of QC is recommended for samples where analytes could be adversely affected by an external homogenization process (i.e. volatile organics). The minimum number of this type of sampling QC, if utilized, is one per sampling event, with a rate of 5 percent to 10 percent commonly used.

– Known Samples - These are reference materials that have been characterized as acceptable to the range of values for the analytes of concern. These materials are available from commercial sources. This type of QC helps determine if the analytical work is sufficiently accurate. It must be noted that improper handling or storage of this type of reference material can invalidate the materials characterization. The minimum number of this type of QC, if used, is one per subject.

- Spiked Samples - These are split/duplicate or replicate samples that have been fortified with the analytes of concern. This QC is intended to determine if there have been changes in concentration due to factors associated with the sample or the shipping and analysis process. This type of QC is very difficult to use in a field environment and routinely is done as part of the analysis process. If this type of QC is necessary, the minimum required is one per project.

- Sample Custody Procedures: Provide information which describes accountability for sample chain-of-custody including sample collector identification, sample location identification, sample number, date and time of collection, parameters to be analyzed, preservatives and fixatives, identification of all couriers, identification of laboratory and receiver, time and date of receipt at laboratory, laboratory analyzer, and time and date of analysis.

- Calibration Procedures and Preventative Maintenance: Equipment maintenance and calibration should be performed in accordance with manufacturer's instructions. Calibration and maintenance sheets should be maintained on file for all equipment.

- Documentation, Data Reduction, and Reporting: Provide discussion on where field data are recorded, reviewed, and filed.

- Data Validation: Provide a discussion and reference to the protocols used for validation of chemical data and field instrumentation and calibration. Describe procedure for validating database fields (i.e., through error checking routines, automatic flagging of data outside of specified ranges, and manual review and spot checking of data printouts against laboratory analytical results).

- Performance and Systems Audits: Provide a description of how field staff performance is checked and how data files are verified for accuracy and completeness.

- Corrective Action: Provide a discussion on what corrections are made when errors are found and actions taken to prevent future recurrence of errors.

- Reports: Provide a list of the types and frequency of reports to be generated (i.e., performance and systems audits, compliance analyses, remediation effectiveness, etc.).

## 4. References

U.S. Environmental Protection Agency, May 1984, Guidance for Preparation of Combined Work/Quality Assurance Project Plans for Environmental Monitoring, (OWRS QA-1), US EPA Office of Water Regulations and Standards.

Mueller, D.K., Schertz, T.L., Martin, J.D., and Sandstrom, M.W., 2015, Design, analysis, and interpretation of field quality-control data for water-sampling projects: U.S. Geological Survey Techniques and Methods, book 4, chap. C4, 54 p.

U.S. Geological Survey, 2006, Collection of water samples (ver. 2.0): U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A4, September 2006.