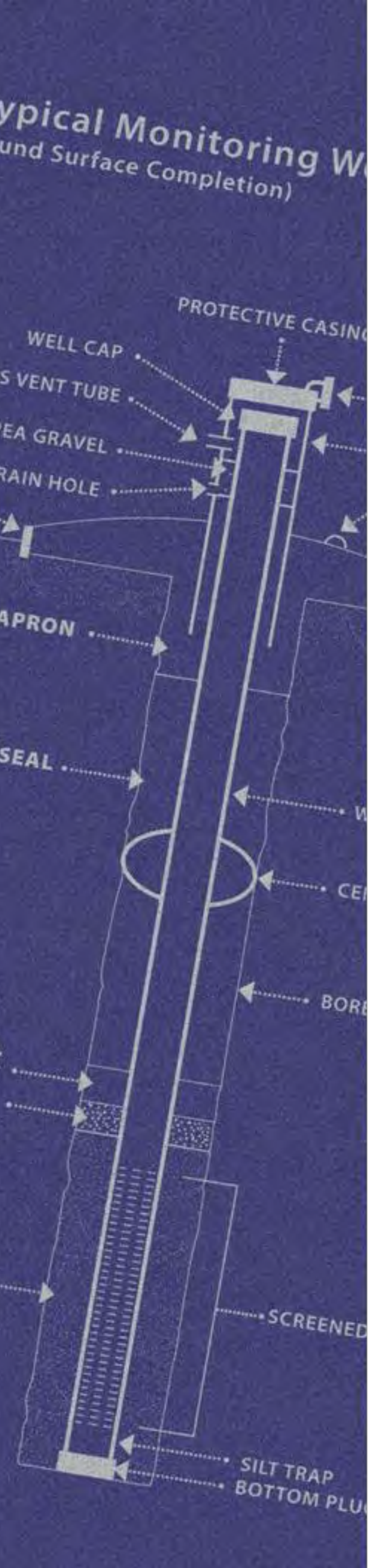

DEPARTMENT OF TOXIC SUBSTANCES CONTROL

CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY

WELL DESIGN AND CONSTRUCTION FOR MONITORING GROUNDWATER AT CONTAMINATED SITES

FINAL ■ JUNE 2014

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FOREWORD

The California Environmental Protection Agency (CalEPA) is charged with the responsibility of protecting public health and the environment. Within CalEPA, the Department of Toxic Substances Control (DTSC) has the responsibility of managing the state's hazardous waste and site cleanup programs. The State Water Resources Control Board (SWRCB) and the nine Regional Water Quality Control Boards (RWQCBs), also part of CalEPA, have the responsibility for coordination and control of water quality, including the protection of the beneficial uses of the waters of the state. Any unauthorized release of a substance, hazardous or not, that degrades or threatens to degrade water quality may require corrective action to protect the beneficial use of the waters of the state.

To aid in characterizing, remediating, and closing hazardous wastes/substances release sites (jointly referred to as contaminated sites in this document), DTSC has developed guidance documents for use by its staff and by other governmental agencies, responsible parties, and their contractors. The Geological Services Branch (GSB) within DTSC provides geologic assistance, training, and guidance. This document has been prepared by GSB staff to provide guidance for the design and construction of groundwater monitoring wells at contaminated sites.

Guidance documents are posted at DTSC's website. For a general overview, please consult: *Guidelines for Planning and Implementing Groundwater Characterization of Hazardous Substance Release Sites* (CalEPA 2012d) and *Preliminary Endangerment Assessment Guidance Manual (A guidance manual for evaluating hazardous substance release sites)* (CalEPA 2013). Other CalEPA guidance documents pertinent to site investigation are listed in *5.0 References*.

This document supersedes the document, released by CalEPA in July 1995:

> *Monitoring Well Design and Construction for Hydrogeologic Characterization, Guidance Manual for Groundwater Investigations.*

Mention of trade names or commercial products does not constitute endorsement or recommendation by DTSC or CalEPA.

Comments and suggestions for improvement of *Well Design and Construction for Monitoring Groundwater at Contaminated Sites* should be submitted to:

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DISCLAIMERS

This guidance document is intended to provide general information to assist with monitoring well design and construction. This guidance document is not legally binding. The word "should" and other similar terms used in this guidance document are intended as general recommendations or suggestions that might be generally applicable or appropriate and should not be taken as providing legal, technical, financial, or other advice regarding a specific situation or set of circumstances. This guidance document is not a rule and it does not create new liabilities or limit or expand obligations under any federal, state, tribal, or local law. It is not intended to and does not create any substantive or procedural rights for any person at law or in equity.

This guidance document discusses other CalEPA guidance documents which may address the exercise of its enforcement discretion on a site-specific basis where appropriate. This guidance document does not address all the circumstances in which CalEPA may choose to exercise enforcement discretion with respect to a party under RCRA or CERCLA, nor does it cover all of the statutory or other protections that may be available to a party at contaminated or formerly contaminated property. This guidance document does not modify or supersede any existing CalEPA guidance document or affect CalEPA's enforcement discretion in any way.

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ACRONYMS AND ABBREVIATIONS

ABS	acrylonitrile butadiene styrene
ANSI	American National Standards Institute
ASTM	ASTM International (formerly known as American Society of Testing and Materials)
bgs	below ground surface
Cal. Code Regs.	California Code of Regulations
CalEPA	California Environmental Protection Agency
CEG	certified engineering geologist
CEQA	California Environmental Quality Act
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CHG	certified hydrogeologist
CMT	continuous multi-channel tubing
COC	chemical of concern
CPT	cone penetrometer test
CSM	conceptual site model
CUPA	Certified Unified Program Agencies
DNAPL	dense non-aqueous phase liquid
DP	direct push
DQO	data quality objective
DTSC	Department of Toxic Substances Control
DWR	Department of Water Resources
ERH	electrical resistance heating
ESI	electronic submittal of information
ESTCP	Environmental Security Technology Certification Program
FEP	fluorinated ethylene propylene
FLUTe™	Flexible Liner Underground Technologies, Ltd. Co
FRP	fiberglass-reinforced plastic
ft	feet
GIS	geographic information system
GSB	Geological Services Branch
HAS	Hazardous Substances Account Act
HASP	Health and Safety Plan
HAZWOPER	Hazardous Waste Operations and Emergency Response Standard
HPT	hydraulic profiling tool
HWCL	Hazardous Waste Control Law
ID	inside diameter
IDW	investigation-derived waste
ITRC	Interstate Technology and Regulatory Council
lb	pound
LNAPL	light non-aqueous phase liquid
m	meter
mg/L	milligrams per liter
MLS	multi-level system

MIP	membrane-interface probe
msl	mean sea level
NAPL	non-aqueous phase liquid
NAVD88	North America Vertical Datum of 1988
NGTF	Nebraska Grout Task Force
NSF	National Sanitation Foundation
NTU	nephelometric turbidity unit
OD	outside diameter
PE	professional engineer
PEA	preliminary endangerment assessment
PFA	perfluoroalkoxy
PFC	perfluorinated compound
PFOA	perfluorooctanoic acid
PFOS	perfluorooctane sulfonate
PG	professional geologist
POTW	publicly-owned treatment works
ppm	parts per million
psi	pounds per square inch
PTFE	polytetrafluoroethylene
PVC	polyvinyl chloride
PVDF	polyvinylidene fluoride
QA/QC	quality assurance/quality control
RCRA	Resource Conservation and Recovery Act
RWQCB	Regional Water Quality Control Board
SCC	shrinkage compensating cement
SDR	standard dimension ratio
SOP	standard operating procedure
SWRCB	State of California Water Resources Control Board
TCE	trichloroethene
TDS	total dissolved solids
TFE	tetrafluoroethylene
TSCA	Toxic Substances Control Act
TSD	treatment, storage, and disposal
USEPA	United States Environmental Protection Agency
VOC	volatile organic compound
WDS	well design specification

1.0 INTRODUCTION

1.1 Purpose and Scope of this Document

The purpose of this guidance document is to present a recommended approach to designing and constructing monitoring wells for groundwater investigations at contaminated sites.

The state-of-practice of environmental characterization has changed substantially since 1995, when the original guidance was released. The intent of this revised guidance is to update the original guidance regarding recent developments and to discuss groundwater monitoring wells within the context of recent developments. In that regard, the overview below provides a thumbnail sketch of the differences between this document and the original guidance.

- *Introduction.* Guidance documents, by CalEPA/DTSC and other parties related to environmental characterization are identified in *1.2 Other Guidance Documents.* Citations frequently used by GSB during document review are included in *1.4 Limitations*.
- *2.0 Planning*. This new section discusses current approaches and technologies used for environmental characterization, and, in particular, for hydrogeological characterization, and places monitoring wells within the context of recent developments.
- *3.0 Monitoring Well Design and Construction* has been updated and new references provided.
- *4.0 Well Casing and Screen Materials* was formerly included in the previous section. Section 4.0 is now presented as a separate section in order to improve the flow of the document. Section 4.0 summarizes the basic research which was conducted in the 1980s and 1990s. The basic research is still valid; therefore, only minor changes have been made to this section.

This guidance was prepared by DTSC staff and has been written with the hope that it will be a useful reference for DTSC project managers and support staff and for other parties (e.g., responsible parties, consultants, and other agencies, including Certified Unified Program Agencies [CUPAs]) engaged in planning site characterization and remedial activities.

<u>Hydrogeological terminology</u>. “Aquifers” are usually defined with respect to production wells for drinking water or for industrial supply and such production wells are designed primarily to maximize yield (i.e., the volume of water extracted). In some regions (e.g., in the Los Angeles Basin and Central Valley), contamination has impacted drinking water aquifers. However, in other regions (e.g., along the margins of the San Francisco Bay), contaminated zones may not be typical aquifers and, in fact, may produce very little water. In this document, “water-bearing zone” is used to refer both to aquifers and

to monitored zones that produce very little water. Similarly, “confining zone” is used in lieu of “aquitard” to signify a zone of relatively low hydraulic conductivity.

Geologic terminology. The word “formation” has a specific meaning in geological terminology: it refers to layers (or strata) that can be readily identified in the field (based on lithology, paleontological features, or similar properties), and is thick and extensive enough to be mapped. Assemblages of formations make up a larger “group”. Formations and groups are all formally-defined and named (e.g., the Tehama Formation, the San Pablo Group). In this document, however, the word “formation” is used informally, to refer to the soil or rock under investigation.

Hyperlinks. Because hyperlinks are temporary, hyperlinks to referenced documents are not provided in this document. Instead, readers are encouraged to use internet search engines to locate the references cited.

1.2 Other Guidance Documents

This document should be used in conjunction with: *Preliminary Endangerment Assessment Guidance Manual (A guidance manual for evaluating hazardous substance release sites)* (PEA Manual: CalEPA 2013). The PEA Manual presents an overview of the site investigation and cleanup process.

Guidelines for Planning and Implementing Groundwater Characterization of Hazardous Substances Release Sites (CalEPA 2012d) provides a broad overview of project planning for groundwater investigations, with emphasis on the Triad approach of: systematic (or strategic) planning, dynamic work strategies, and real-time measurement systems. More information is available at Triad Central website.

A multi-media approach to site characterization is recommended for most sites, and other guidance documents should be consulted. For example, human health risks due to vapor intrusion from the subsurface to indoor air must be evaluated if volatile organic compounds (VOCs) are chemicals of concern (COCs) at a site. To assess the vapor intrusion-to-indoor air pathway, groundwater, soil, and soil gas investigations are usually required. The design and installation of soil gas monitoring probes are addressed in the *Soil Gas Advisory* (CalEPA 2012a). Other CalEPA/DTSC guidance documents addressing: groundwater sampling, soil sampling, geophysical tools, drilling and logging, groundwater modeling, and aquifer tests are listed in *5.0 References* and/or are posted on DTSC’s website.

Other parties who provide guidance documents include: United States Environmental Protection Agency (USEPA); ASTM International (formerly, the American Society of Testing and Materials); Interstate Technology and Regulatory Council (ITRC); organizations (e.g., National Groundwater Association); and, other agencies (e.g., State of Ohio Environmental Protection Agency).

CalEPA/DTSC is striving to keep up-to-date with external guidance and with new technologies. As new technologies are developed and gain acceptance, and as existing technologies are augmented or refined, CalEPA/DTSC documents will be updated.

No guidance document can account for every possible variation that may exist at every contaminated site. The selection and application of any method or tool is the responsibility of personnel overseeing and conducting the studies. Training and experience are required and independent judgment should be exercised where needed.

Comprehensive guides to designing wells and choosing appropriate drilling techniques include: *Practical Handbook of Environmental Site Characterization and Groundwater Monitoring* (Nielsen 2006); *Groundwater & Wells* (Sterrett 2007, and earlier edition: Driscoll 1986); *Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells* (Aller et al.1989); *Handbook of Ground Water Development* (Roscoe Moss Company 1990), among others. ASTM standards related to well design and installation (e.g., ASTM 2010a, ASTM 2010b, ASTM 2012a) are mentioned throughout this document.

1.3 Overview of Regulatory Cleanup Process

Investigation and cleanup of contaminated sites may be governed by one of several federal or California laws, including but not limited to:

- Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA);
- Resource Conservation and Recovery Act (RCRA);
- Hazardous Waste Control Law;
- Hazardous Substances Account Act;
- California Environmental Quality Act (CEQA); and
- Toxic Substances Control Act (TSCA).

The laws applicable to a given site depend on such factors as the source, cause of the release, and cleanup process under which the site is being addressed. For example, school sites have additional requirements, and RCRA-permitted sites may have specific regulatory requirements. In addition to state and federal requirements, readers should determine whether more stringent local codes/requirements apply, such as local well or boring permits, which may vary from region to region. A list of local agency contacts for well construction and decommissioning is provided on the DWR website.

While every site has a unique set of technical, logistical, and budgetary constraints that affect execution of the investigation, in the broadest sense, every site investigation follows similar processes for scoping and planning field investigations and selecting a final remedy. If action is necessary to immediately protect public health and/or the environment, emergency or interim measures may be taken at any point in the process. Public participation is required at various stages during the process.

Site investigations should be conducted by professionals with education in engineering, geology, or related sciences, and several years of experience in the environmental field. For some activities, the signatures of licensed professional engineers and/or geologists (i.e., PEs and/or PGs) are required by the California Business and Professions Code and the California Health and Safety Code. Professionals with education and experience in chemistry, microbiology, toxicology, and other sciences, as well as engineering specialists, should be considered for inclusion on a project team as appropriate.

It is the obligation of the responsible parties and qualified professionals performing site investigations to consult with regulatory agencies and identify and comply with all pertinent requirements.

1.4 Limitations

This guidance document focuses on a typical groundwater monitoring well (i.e., a single-casing well with a short screened interval). Some other well-types are mentioned but are not discussed in detail (e.g., direct push wells, nested wells, well clusters, multi-level systems, and horizontal wells). Some types of wells are beyond the scope of this document—for example, extraction wells, injection wells, and wells for thermal applications (e.g., electrical resistance heating [ERH] wells): these wells require specialized design expertise.

This document does not define standard operating procedures (SOPs) for well construction and material selection. The qualified professional in responsible charge of the field investigation should specify the methods, equipment, and operating procedures in a work plan and document any significant departures from the work plan that were implemented during the course of the investigation.

A well design should be developed with respect to the well's function within a well network. However, design of well networks is outside the scope of this document.

This document does not supersede statutes and regulations. State regulations and ordinances which address monitoring well design and construction include, but are not limited to:

- Department of Water Resources (DWR), *Bulletin 74-90 (Supplement to Bulletin 74-81): California Well Standards, Water wells, Monitoring wells, Cathodic protection wells, June 1991*;
- California Code of Regulations (Cal. Code Regs.), Title 22, Division 4.5, Chapter 14, Article 6, *Environmental Health Standards for the Management of Hazardous Waste*;
- Cal. Code Regs., Title 23, Division 3, Chapter 15, Article 4, *Regulations of the State Resources Control Board and Regional Water Quality Control Boards*; and
- California Business and Professions Code, Division 3, Chapters 7 and 12.

A summary of state laws is presented in DWR's booklet: *California Laws for Water Wells, Monitoring Wells, Cathodic Protection Wells, and Geothermal Heat Exchange Wells* (DWR 2003).

Some citations relevant to well design and construction are:

- "All geologic plans, specifications, reports, or documents shall be prepared by a professional geologist or registered certified specialty geologist, or by a subordinate employee under his or her direction. In addition, they shall be signed by the professional geologist or registered certified specialty geologist or stamped with his or her seal, either of which shall indicate his or her responsibility for them." *Geologist and Geophysicist Act* (Business and Professions Code Chapter 12.5, Article 1, §7835)
- "Construction, alteration, or destruction of monitoring wells to monitor hazardous waste facilities, other waste facilities, or underground storage tanks, shall be performed under the supervision of a California Registered Professional Engineer, California Registered Geologist, or California Certified Engineering Geologist, where specified by law." (*California Well Standards, Bulletin 74-90*, Part 1, Article 6)
- "In some cases, it may be necessary for a local enforcing agency to substitute alternate measures or standards to provide protection equal to that otherwise afforded by DWR standards. Such cases arise from practicalities in applying standards, and from variations in geologic and hydrologic conditions. Because it is impractical to prepare 'site-specific' standards covering every conceivable case, provision has been made for deviation from the standards." (*California Well Standards, Bulletin 74-90, Limitations*)
- "Ultimate responsibility for the design and performance of a monitoring well rests with the well owner and/or the owner's contractor, and/or technical representative(s)." (*California Well Standards, Bulletin 74-90, Limitations*)
- "All monitoring systems shall be designed and certified by a registered geologist or a registered civil engineer." (Cal. Code Regs. §66264.97 (e) (1))
- "All monitoring wells and all other borings drilled to satisfy the requirements of this article shall be logged during drilling under the direct supervision of a registered geologist. These logs shall be submitted to the Department upon completion of drilling." (Cal. Code Regs. §66264.97 (e) (2))
- "Persons responsible for construction, alteration, destruction, or abandonment of monitoring wells must possess a C-57 Water Well Contractor's License." (California Water Code, Division 7, Chapter 10, Article 3, §13750.5)
- "Every person who digs, bores, or drills a water well, cathodic protection well, groundwater monitoring well, or geothermal heat exchange well, abandons or destroys such a well, or deepens or reperforates such a well, shall file with the department a report of completion of that well within 60 days from the date its construction, alteration, abandonment, or destruction is completed. The report shall be made on forms furnished by the department [DWR]." (California Water Code §13751 (a) and (b))

- “Every person owning land in fee simple or in possession thereof under lease or contract of sale who knowingly permits the existence on the premises of any permanently inactive well, cathodic protection well, or monitoring well that constitutes a known or probable preferential pathway for the movement of pollutants, contaminants, or poor quality water, from above ground to below ground, or vertical movement of pollutants, contaminants, or poor quality water below ground and that movement poses a threat to the quality of water of the state, shall be guilty of a misdemeanor.” (Health and Safety Code, Division 104, Part 9.5, §115700 (b))

Readers should determine whether these citations apply to their particular situations. For example, the second bullet applies to all monitoring wells while the fifth and sixth bullets apply to specific RCRA-regulated units (i.e., hazardous waste land disposal units).

Federal, state, and local regulations, statutes, and ordnances for well construction should be identified, and site characterization activities should be performed in accordance with the most stringent applicable, or relevant and appropriate requirements.

2.0 PLANNING

2.1 Hydrogeologic Characterization Objectives

The broad objectives of hydrogeologic characterization of contaminated sites are to determine:

- The nature and extent of contaminants in groundwater at the site;
- The geology and hydrogeology beneath and surrounding the site; and
- The fate and transport of contamination.

Site characterization has advanced substantially over the last two decades. Technologies that are commonly used today include: various geophysical tools, cone penetrometer tests (CPTs), membrane interface probes (MIPs), hydraulic profiling tools (HPTs), and other direct push (DP) methods. Moreover, new tools are under development (e.g., field-based analytical methods) and existing tools are continually improving (e.g., new sensors for DP methods). However, review of available technologies is outside the scope of this document. For an overview of hydrogeological characterization, readers are encouraged to consult: *Planning and Implementing Groundwater Characterization of Hazardous Substance Release Sites* (CalEPA 2012d). For detailed discussions, Nielsen (2006) is recommended.

As site characterization technologies have evolved, along with an increased understanding of the complexity of the subsurface, the role of groundwater monitoring wells has also changed, as described in *2.4 Purposes of Monitoring Wells* and in *2.5 Characterization versus Monitoring*. In particular, monitoring wells are more often installed later in the investigative process. And, data from groundwater monitoring wells are used to confirm and complement data obtained using other tools. The combined data set is used to meet the objectives of hydrogeologic characterization.

This document addresses groundwater monitoring wells. However, it must be emphasized that information collected from groundwater monitoring wells will not be sufficient to characterize a site for risk assessment or for remedy selection. A multi-media investigation will be required at most sites, which may include sampling of soil, soil gas, indoor air, and surface water (CalEPA 2012d).

2.2 Conceptual Site Model

Existing information on a site is summarized in a conceptual site model (CSM). A CSM utilizes multiple sources of data (e.g., groundwater monitoring wells, other investigative tools, and data from other media), as well as information about historical practices and potential future uses from interviews and public documents. The CSM identifies

chemicals of concern (COCs) in all media and identifies potential receptors and exposure pathways.
The CSM is the platform on which work plans are constructed. Work plans should include a section which presents and discusses the CSM and explains how the proposed investigation will refine the CSM and/or fill CSM data gaps.

The CSM evolves as site investigation proceeds. For example, at the start of a site investigation, the preliminary CSM strategy may be to identify potential COCs and to evaluate general site features as potential sources of contamination, using site history (e.g., photos, floor plans, interviews) and screening-level technologies (e.g., grab groundwater sampling or composite soil sampling). As the site investigation matures, the CSM will comprise more detailed and comprehensive knowledge necessary for risk assessment and remedy selection (e.g., groundwater monitoring well data). During the design phase, the CSM may focus on data needed for remediation design optimization and performance monitoring (e.g., in situ treatability studies). The CSM life cycle is discussed in CalEPA (2012d) and USEPA (2011).

The hydrogeologic portion of the CSM should include cross-sections: a block diagram or fence diagram is also recommended.

2.3 Data Quality Objective (DQO) Process

The DQO process is a planning process that allows users to determine the type, quality, and quantity of data that will be sufficient for decision-making. The work plan for design and installation of monitoring wells should include a section on the DQO process. The DQO process is described in detail in *Guidance on Systematic Planning Using the Data Quality Objectives Process EPA QA/G-4* (USEPA 2006).

The DQO process consists of iterative steps which include narrative descriptions and quantitative criteria, such as:

- A description of the environmental problem that initiated the study;
- A description of the CSM;
- The decisions that need to be made and inputs to the decision;
- The type, quality, and quantity of data needed;
- The decision rules for the investigation, usually expressed as “if … then” statements; and,
- An explanation of how the data will be used.

The DQO process establishes specific performance or acceptance criteria, known as data quality objectives or DQOs.

As part of the DQO process, specific purposes and anticipated uses of each monitoring well should be identified, as purposes/uses may vary throughout the well network and within the lifetime of each well. For example: Will the well be used solely as a piezometer (i.e., to measure groundwater elevations)? Will the well be used to delineate the extent of a plume? Will the well be used as a point-of-compliance at which accurate concentrations are critical for determining regulatory compliance? Will the well be used to extract contaminated groundwater as part of remedial action activities?

The purposes of the monitoring well should guide the well design. For example, if the well is to be used solely to monitor the edge of a plume or to measure water elevations, then direct-push installation of a 2-inch diameter well with a pre-packed screened interval may be appropriate. If the well is a RCRA point-of-compliance (e.g., at a landfill), then a 4-inch diameter well with a short well screen may be required. If the well may be used for injection and/or extraction, then strength and well efficiency may be critical design factors. If wells may serve multiple purposes, the most critical purposes that are driving the well design should be identified.

Environmental factors such as freezing or hot/dry conditions, flooding, and flowing artesian conditions should also be considered during well design. Local ordinances for well construction should be reviewed because these may be based on local environmental conditions. Potential impacts of climate change—including: extreme precipitation events, flooding, wildfires, sea level rise, and salt water intrusion—should also be considered when locating and designing wells.

Because wells are not permanent structures, the projected lifetime of a well should be considered during well design and incorporated into the work plan, along with well maintenance and the eventual decommissioning of the well.

In addition to a description of the DQO process, quality assurance/quality control (QA/QC) measures for well installation, development, water elevation measurements, sampling, and aquifer testing should be presented in the work plan.

If the work plan involves multi-media sampling or the use of various sensing technologies, each media and technology should be addressed separately in the DQO process.

2.4 Purposes of Monitoring Wells

The purposes of monitoring wells are:

- Provide representative groundwater samples to assess groundwater quality over a period of time (e.g., to evaluate remediation effectiveness, to assess permit compliance, or to determine contaminant plume dynamics such as seasonal variations in water levels and COC concentrations);
- Obtain hydraulic head information to estimate groundwater flow directions, gradients (horizontal and vertical), and velocities;
- Conduct aquifer tests and estimate aquifer hydraulic properties;
- Provide estimates of mass flux and mass discharge; and,

- Determine lithology (e.g., through examination and description of continuous cores).

Wells should be designed and located to refine the CSM or to fill specific data gaps in the CSM. It is unusual for a well to fulfill all the purposes listed above. For example, if it is necessary to determine the extent of light non-aqueous phase liquids (LNAPLs or “floaters”) in a shallow aquifer, the well screen should intersect the water table. However, if dense non-aqueous phase liquids (DNAPLs or “sinkers”) may be encountered, it may be appropriate to locate the well screen above an underlying clay unit. Wells designed to monitor LNAPL or DNAPL may not be appropriate for aquifer tests.

For aquifer tests, fully-penetrating well screens (i.e., screens that cross the full thickness of the aquifer) might be considered because fully-penetrating well screens are assumed in some equations used to estimate hydraulic properties. However, the potential for vertical cross contamination should be evaluated prior to installing fully-penetrating well screens. Solutions for partially-penetrating screens can also be considered.

All monitoring wells must:

- Prevent infiltration of surface water into the well, and
- Prevent cross-contamination within water-bearing zones and between water-bearing zones.

DWR (1991) provides *minimum* standards for the design, construction, maintenance, and destruction of wells to prevent contamination of groundwater. ASTM (2010a), which provides standards for design and installation of wells, is updated as needed.

The well design should be developed with respect to the well’s function within a well network. The design of well networks is outside the scope of this document and is not discussed further. However, two examples that relate the design of monitoring wells to the well network are provided. Example 1: a well network for a volatile organic compound (VOC) plume might include wells within areas of higher concentration, upgradient wells, and downgradient wells. The VOC well network might be arranged in transects parallel to and perpendicular to the axis of the plume. However, each well within the network might be designed differently depending on the well’s purpose. For example, direct push wells might be specified for short-term wells on the edge of a shrinking plume and multi-level wells might be specified for long-term monitoring of in situ remediation or of monitored natural attenuation. Example 2: the well system for an aquifer test should be designed so that potential migration of contaminants during pumping is controlled, especially if drinking water wells are located nearby. Sara (2006) discusses well networks.

Groundwater monitoring wells and monitoring networks should be designed by a California-licensed professional geologist (PG) or a professional engineer (PE, Civil), with experience in hydrogeology.

Monitoring wells and borings should be logged during drilling under the direct supervision of a PG. The PG's signature on the logs will document that this recommendation has been met.

Persons designing wells and networks should consult Business and Profession Code §6700 et seq. and §7835 et seq. for the applicability of licensing and registration requirements.

Well names and numbers are permanently assigned and should never change. The approach to naming and numbering wells should be carefully considered. Sequential names and numbers are often used and are easily understood (e.g., MW1, MW2, MW3). Well names should signify special functions—for example, for extraction wells, an "E" could be included in the well name (e.g., EW1, EW2). The names and numbers of replacement wells should signify that they are replacement wells—for example, by adding an "R" to the well name (e.g., MW1R, MW2R).

Well and boring information for each site should be organized in spreadsheets. It is beneficial to format well coordinates, elevations, and other well-specific data (Sections 3.14 and 3.17) in a way that allows for data manipulation within a database (e.g., as required for GeoTracker), or, for complex sites, within a geographic information system (GIS). Logs should be attached to the database. The database should be updated when wells are altered or decommissioned (Sections 3.18 to 3.20), or when new wells or borings are installed. Revised databases should be provided to the enforcing agency. Tables containing well and boring information should be included in reports.

A searchable database for wells and borings should be developed for each site, containing detailed construction and installation information (see Sections 3.14 and 3.17), along with alteration and decommissioning information (see Sections 3.19 and 3.20). Logs should be attached to the database. The database should be updated when new wells or borings are installed and provided to the enforcing agency.

2.5 Characterization versus Monitoring

The function of monitoring wells has changed significantly in the last couple of decades as understanding of the complexity of the subsurface has advanced and as site characterization approaches and technologies have evolved. Previously, monitoring wells were used for early site characterization. Currently, site characterization is often conducted using tools other than monitoring wells, and monitoring wells are installed later in the process, as discussed below. The CSM evolves by combining results from monitoring wells with hydrogeological data which are acquired using a variety of tools, along with data from other media.

Subsurface contamination is now known to be more heterogeneous than previously assumed (Nielsen et al. 2006). Thin narrow plume cores (less than 20 feet wide), emanating from residual NAPL sources, are now believed to convey the majority of contaminant mass at many sites. In a landmark study, Guilbeault et al. (2005) determined that 85 percent of contaminant mass flowed within just 15 percent of the cross-sectional area of the dissolved plume. Several discrete plume cores may exist within the footprint of a larger dissolved plume. Plume cores may continue for considerable distances without significant attenuation (van der Kamp et al. 1994). The concept of plume cores (defined by high-resolution investigative techniques) has replaced to some degree the previous concept of a hotspot (which was often defined by a single monitoring well).

Characterization and treatment of plume cores has become the focus of investigation and remediation at many sites. To delineate plume cores, vertical sampling at close intervals (aka profiling) along transects perpendicular to the plume axis is conducted using high-resolution tools (e.g., DP methods or multi-level systems) (Einarson 2006). The use of transects is promoted by the regulatory community (USEPA 2004), by industry (API 2003), and by others (Einarson et al. 2010).

Plume cores delineated by high resolution techniques exhibit complex 3D distribution patterns, with: variable rates of mass loading, limited mixing of dissolved solutes, and spatially-variable attenuation mechanisms. COC concentrations may vary by orders-of-magnitude over just a few feet, especially in the vertical direction (Nielsen et al. 2006). Strong variations in vertical head distribution have been observed. Vertical profiling: helps identify zones for targeted remediation; provides feedback on remediation effectiveness; and facilitates estimates of mass flux and mass discharge (which are important risk metrics) (ITRC 2010).

The density of data collected using high resolution methods far surpasses the density of data previously acquired using monitoring wells. Interactive visualization and data management systems allow the manipulation and illustration of data in 3D. For example, 3D plume displays are a substantial improvement over 2D plume maps previously developed using monitoring well data. And, on cross-sections, lithologic data from well logs can be combined with soil behavior types from CPTs, and other information (e.g., from HPTs), to develop a more robust and detailed hydrogeological CSM.

Previously, groundwater monitoring wells were installed early in the investigative process (e.g., one well located upgradient and two or three wells located downgradient). Today, groundwater monitoring wells are installed later in the investigative process. The selection of well locations and screened intervals is guided by earlier DP and high resolution investigations. Now, wells are more often used: to monitor trends, to assess whether closure criteria are satisfied, and to evaluate remedial actions.

However, typical monitoring wells (individually or in clusters) are still used for site characterization in situations where other approaches (e.g., DP methods) are not possible, practical, or cost effective (e.g., in deep groundwater or fractured bedrock), or where required by law (for RCRA land disposal units), or where an understanding of the 3D hydraulic head is needed early in the investigation (e.g., in areas with radial flow).

When the first version of this guidance was published in 1996, the focus of the document was on a single-bore well with a single screened interval (referred to as a typical monitoring well). The typical monitoring well continues to be the focus of this document; however, the discussion has been expanded and sections have been added to reflect changing practices. For example, direct push (DP) wells, horizontal wells, and multi-level wells/systems are briefly discussed in *2.7 Types of Monitoring Wells*.

2.6 Sealing Confining Layers

During monitoring well installation, it may be necessary to drill through confining layers (i.e., zones of low permeability [e.g., clays and silts] or aquitards). To meet the requirements of DWR (1991), drilling through a confining layer must not create a conduit for contaminant migration between hydraulically-separated water-bearing zones.

The following approaches for drilling through confining layers should be considered.

- Drill initial boreholes on the perimeter of the site (in less contaminated or uncontaminated areas). These borings could penetrate the confining layer to provide information on the confining layer, as well as deeper units. Boreholes upgradient of the source could also be drilled through the possible confining layer to characterize site geology. The appropriateness of this approach must be evaluated on a site-specific basis.

- Drill boreholes using methods and techniques that minimize the danger of cross-contamination between water-bearing zones. Such techniques typically involve drilling a borehole partially into the confining layer, installing a conductor casing, sealing the annular space between the conductor casing and the borehole wall, and drilling a smaller diameter borehole through the confining layer.

- DP methods that may penetrate confining layers include DP well installation (dual-walled only), as well as single- and dual-walled probing, real-time measurement tools, and sampling tools. In each case, proper grouting protocols and materials should be employed to minimize the potential for contaminant migration between water-bearing zones.

  Information on direct push methods is available in:

  - *Expedited Site Assessment Tools for Underground Storage Tank Sites, A Guide for Regulators*. *EPA 510-B-97-001*. USEPA. March 1997.
  - *The Use of Direct Push Well Technology for Long-term Environmental Monitoring in Groundwater Investigations*. ITRC 2006.
  - *Use of Direct Push Technologies for Soil and Ground Water Sampling*. Chapter 15 in *Technical Guidance Manual for Ground Water Investigations*. State of Ohio Environmental Protection Agency. February 2008.

- *Techniques for Sealing Cone Penetrometer Holes*. Lutenegger, Alan J. and DeGroot, Don J. Can. Geotech. J. 32: 880-891. 1995.

2.7 Types of Groundwater Monitoring Wells

Brief descriptions of wells are provided below. Various types of groundwater monitoring wells, including multi-level wells, are discussed in detail in Nielsen (2006).

2.7.1 Typical Groundwater Monitoring Wells

This guidance focuses on the design and installation of a typical groundwater monitoring well, which is defined as a single-casing well with a short screened interval of 10 feet or less (Figure 1). (The length of the screened interval is further discussed in Section 2.7.1.1).

A detailed discussion on design and installation of typical groundwater monitoring wells is provided in *3.0 Monitoring Well Design and Construction*. However, general discussions and recommendations in Section 3.0 may apply to other types of groundwater monitoring wells and to piezometers designed and installed for water elevation monitoring at contaminated sites.

Technologies that may improve sampling of groundwater monitoring wells are in development. For example, the Zone Isolation Sampling Technologies (ZIST™) by BESST, Inc. is a downhole assembly that combines a packer and a pump (with sensor options) (Kueper et al. 2014). ZIST™ isolates the screened interval, thereby reducing purging volumes and associated waste disposal costs.

2.7.1.1 Long-Screened Wells

Long-screened wells are typical groundwater monitoring wells that have longer screens (i.e., screens are longer than about 10 feet). Recently, long-screened wells have been topics of heightened interest, and so, an expanded discussion is included here.

Wells with long screen lengths may facilitate cross-contamination between contaminated zones, especially when high concentrations of COCs are confined to relatively thin water-bearing zones and vertical hydraulic gradients are present. Therefore, long screens are generally discouraged. In particular, long screens should not be used in source areas, especially where DNAPL is present.

Vertical profiling of COC distribution and hydraulic head at many sites shows significant variability of COC distribution and hydraulic head over distances of just a few feet (as discussed in Section 2.5). At sites where DP methods can be used, vertical variation in COC concentration and head distribution can be determined in early DP investigations

(McCall et al. 2006). Results of DP investigations can then be used to specify well screen lengths that match the scale of the affected zones (which will be generally less than 10 feet) (ESTCP 2008, Nielsen et al. 2006). If multiple monitoring wells with short well screens are necessary to span the zone of interest, a cluster of wells (Section 2.7.2.1) or a multi-level system (Section 2.7.2.3) can be installed.

With long-screened wells, water-bearing zones with highest hydraulic head (i.e., water pressure) will be preferentially purged and sampled and, therefore, the resulting samples are considered to be composite samples. Such composite samples: will not reflect the range of concentrations in the screened interval; may not represent average concentrations; and, may be variable in time. If the zone with the highest head is the most contaminated zone, the composite sample may overestimate the concentration of the long-screened interval. Conversely, if the zone with the highest head is the least contaminated zone, the composite sample may underestimate the concentration of the long-screened interval (Einarson 2006; McIlvride and Rector 1988). Consequently, composite samples from long-screened wells may not be acceptable for RCRA detection or compliance monitoring.

A long-screened well, by re-distributing contaminants between zones, may: confound efforts to delineate contamination and to trace contamination back to its source; increase the depth of the contamination and the volume of groundwater requiring cleanup; and, potentially threaten previously unaffected aquifers and receptors (Einarson 2006).

Due to dilution of the groundwater sample, risks associated with groundwater or with vapor intrusion may be underestimated. However, in some cases, samples from long-screened wells may lead to overestimation of risks to receptors. For example, if a layer of shallow uncontaminated groundwater overlies the plume (but is not detected in samples from a long-screened well), vapor intrusion risks may be overestimated (Einarson 2006).

Water level elevations from long-screened wells will preferentially reflect the water-bearing zone within the screened interval that has the highest transmissivity (McIlvride and Rector 1988). The transmissivity of a water-bearing zone is its hydraulic conductivity multiplied by the height of the zone. Therefore, water level elevations will not represent average water level elevations over the screened interval, and water level contour maps (or potentiometric maps) drawn with water elevations from long-screened wells may be inaccurate.

Long screens may be acceptable in areas of low hydraulic conductivity (e.g., thin discontinuous interbedded silts and clays or fractured bedrock), if vertical gradients are negligible. However, long-screened wells should be used with caution, because even slight vertical gradients may have significant impact and because vertical gradients may change in time (e.g., due to starting or stopping of pumping) and cross-contaminating conditions may develop.

Long-screened wells may also be appropriate in areas where water level elevations change substantially on a seasonal or annual basis (e.g., due to local pumping for remediation or irrigation, or to natural forces, like tides or extreme wet/dry cycles).

If the long well screen crosses the entire aquifer (or a significant thickness of an aquifer), vertical profiling is sometimes used to estimate COC distribution (e.g., using passive sampling techniques, grab samplers, or depth-discrete pumping). However, even a slight vertical gradient within the long-screened well may cause mixing of water from different zones and cross-contamination between zones (Elci et al. 2001; Elci et al. 2003). Elci et al. (2001) observed significant vertical flow in 73% of 142 wells, using sensitive borehole flowmeters. Because of the potential for vertical flow within the well and other factors, vertical profiling results from long-screened wells may be ambiguous and of limited utility: that is, the COC vertical profile within the well may be different than the COC vertical profile in the aquifer.

Existing long-screened wells may need to be evaluated (Section 3.19) to determine if cross-contamination between water-bearing zones is occurring. If cross-contamination is occurring, decommissioning may be required.

Some existing deep wells constructed in open boreholes (e.g., in indurated rock) have surface seals but are uncased and unsealed below the surface seal. Wells constructed in this manner raise the same concerns as long-screened wells. In particular: the potential for vertical migration of contaminants may exist; samples from such wells are considered to be composites; and, water pressure measurements may be difficult to interpret. Such wells should be evaluated (Section 3.19) and may need to be retrofitted, abandoned, or replaced. Methods for preventing cross-contamination and for sealing such wells include installation of FLUTe™ liners or construction of multi-level wells within the open borehole (Sterling et al. 2005).

2.7.1.2 Inclined (or Angled) Wells

Inclined wells are typical groundwater monitoring wells that are not plumb (i.e., they are installed at an angle to the vertical). Inclined wells may be used to avoid utilities or to reach under a building or an operating facility. Installation of the filter pack and annular seal may be difficult. In addition, well decommissioning may be problematic.

2.7.1.3 Direct Push (DP) Wells

Direct push (DP) wells are similar in overall design and construction to typical groundwater monitoring wells (Figure 1), except that: diameters of the borehole and the well casing are generally narrower; pre-packed well screens may be used; and, the well installation method is different.

DP wells are small-diameter PVC pipes or hollow steel rods that are pushed, driven, or vibrated into the ground. DP wells can be installed in a cluster or as inclined wells and can used as piezometers. DP wells installed in unconsolidated sediments can often be advanced to depths of 150 feet. Below about 150 feet, direct push methods may not be feasible, unless installed in combination with other drilling methods—for example, inside a hollow stem auger (HSA). Direct push methods (unless combined with other drilling methods) are unsuitable for coarse, consolidated, cemented or lithified deposits, bedrock, and municipal or hazardous waste.

Care must be taken during installation to ensure an adequate bentonite seal and annular seal. Recently-developed bentonite sleeves may reduce the potential for vertical cross-contamination (Major et al. 2009). Shorter screens also reduce the risk of cross-contamination. Inclinometer readings can be specified to ensure plumbness, especially for deeper installations.

Some advantages of DP wells, when compared to wells installed using other drilling methods, are faster installation and reduced waste (i.e., from soil cuttings, development water, and purge water). Therefore, DP wells may be more economical than typical groundwater monitoring wells. Also, because less waste is generated, worker exposures are reduced. ESTCP (2008) presents life-cycle cost comparisons between DP wells and HSA wells.

In the ESTCP project report (Major et al. 2009), DP wells were compared to HSA wells and pre-packed DP wells (Section 3.8.3) to no-pack DP wells. Results for DP wells and HSA wells (i.e., matched pairs) were generally comparable with respect to chemical analytical data (organic and inorganic), purge parameter data, and hydrogeological tests. Low flow (i.e., low stress) sampling protocols were used. Purge parameters having least agreement between DP and HSA wells were turbidity and dissolved oxygen. Statistical variability was attributed more to spatial heterogeneity than to well type. Major et al (2009) advocated the use of commingled data from DP and drilled wells and the use of DP wells for long-term monitoring.

ESTCP's hydrogeological tests (i.e., unsteady and steady state pump tests, and rapid pneumatic slug tests) were conducted in high permeability formations, and therefore, results may not fully apply to low permeability formations. Because pumping stresses on the well casing and well screen increase as the tightness of the formation increases, DP well components may need to be designed with higher strength (e.g., schedule 80 casings , wire-wrapped stainless steel screens) if pump tests are to be conducted in DP wells in low permeability formations.

DP technology can be used for grab groundwater sampling and for collecting a wide variety of data. DP tools can be used for continuous measurement of contaminant distribution and geotechnical characteristics.

More information on DP methods is provided in *Groundwater Sampling and Monitoring with Direct Push Technologies* (USEPA 2005) and in ASTM (2010c), ITRC (2006), Ohio (2008), USEPA (2005), and Lutenegger and DeGroot (1995).

2.7.1.4 Horizontal Wells

Horizontal wells have been used for decades in the oil industry and in utility installation and replacement, but are relatively new in the environmental field, where they are currently used for remediation—as opposed to characterization or monitoring. However, horizontal well technology is continually improving and, in the future, horizontal wells may also be used for characterization and monitoring (e.g., for post-remediation monitoring).

Horizontal wells have two components: inclined or vertical components and horizontal components. The vertical or inclined component curves into the horizontal component at a specified depth. Pull-through wells or pull-back wells have two vertical/inclined components. The inclined or vertical components are blank casing. The horizontal component contains a long screen, which may be hundreds of feet long.

Inclined or vertical components resemble typical monitoring wells. The inclined/vertical components may cross several hydrogeological zones and require annular seals. Horizontal components are generally installed within one hydrogeological zone. Therefore, for horizontal components, an annular seal is not installed and a natural filter pack is developed.

Installation of the horizontal component is usually by mud-rotary drilling. Typical installation entails: 1) a pilot hole is drilled along the designed horizontal path; 2) the pilot hole is reamed until the design diameter is achieved; and, 3) the pre-fabricated horizontal pipe is pulled back through the reamed hole. Horizontal components may also be configured radially around a central vertical component. Gridded or site-perimeter designs have also been used.

Current remedial applications include: groundwater and soil vapor extraction, dual-phase extraction, soil vapor mitigation, air sparging, hydraulic/pneumatic control, cathodic protection, and injection (e.g., for bioremediation, metals stabilization, and chemical oxidation). Horizontal components are also used in some soil heating approaches.

Advantages include:

- Horizontal components can be installed in locations where vertical wells are not allowed or are difficult to install (e.g., around subsurface obstacles; within air fields or high-security facilities; in environmentally sensitive areas; and under buildings, utilities, railroads, water courses, and rights-of-way);
- Precise emplacement of horizontal components is ensured by directional drilling of the pilot test hole (e.g., using hand-held radio-detection equipment);
- The hydraulic/pneumatic zone of influence extends over a larger groundwater/soil vapor volume (i.e., when compared to the zone of influence of a vertical well);
- Amendments and reagents are delivered over a larger soil volume (i.e., when compared to the smaller soil volume associated with the screened interval of a

vertical monitoring well);
- Horizontal components can be installed within a specific stratigraphic zone (e.g., within a source area or along the axis of a plume);
- Horizontal wells can be used more effectively than vertical wells in thin aquifers for remediation and pumping, because vertical wells may not provide sufficient saturated thickness for remedial efficacy;
- Horizontal components can be installed under active facilities without disrupting operations; and,
- Because of the greater contact with subsurface media, the time to reach closure criteria may be decreased.

Disadvantages include:

- Horizontal wells can provide paths for contaminant migration, and, because screen lengths are long, the potential for contaminant migration (e.g., in DNAPL zones) must be carefully evaluated;
- Well design requires specialized expertise (e.g., the design of the well screen must ensure uniform flow over the entire length of the screen, and tensile strength, compressive strength, and collapse strength must be specified);
- Mud-rotary installation of horizontal components requires specialized expertise (e.g., drilling muds must avoid damage to the formation and ensure effective communication with the formation);
- Long lengths of pipe are required to achieve the specified depth for the horizontal component (e.g., the inclined component must be about 100 feet long to reach a depth of 30 feet);
- Geotechnical investigations (e.g., CPTs) prior to design are generally required;
- Development, maintenance, and reconditioning is difficult and may be expensive; therefore, horizontal wells may have shorter life spans when compared to vertical wells;
- Decommissioning may be difficult;
- Soil sampling along the horizontal length of the well is possible but costly and difficult due to the long pipe lengths;
- The volume of waste for disposal is large due to the mud rotary drilling technique and the long pipe runs; and,
- Horizontal wells may not be allowed by regulatory agencies, including local agencies.

2.7.2 Multi-Level Monitoring Wells/Systems

Awareness of the spatial variability of COCs and head distribution at contaminated sites has led to an increase in the number of multi-level monitoring wells or systems in California. Multi-level wells and systems are screened at various discrete depths. All such systems are designed to:

- Yield multiple, depth-discrete groundwater samples;

- Allow depth-discrete measurements of hydraulic head; and,
- Prevent vertical flow between the monitored intervals.

Typical monitoring wells can be constructed in clusters or nests to yield multi-level data. Several engineered multi-level monitoring systems (MLSs) are commercially available. A brief overview of multi-levels monitoring wells is presented below. A detailed description of various technologies for multi-level groundwater sampling and monitoring is presented by Einarson (2006).

2.7.2.1 Well Cluster

Cluster wells are groups of individual monitoring wells that: are located close together; are installed in separate boreholes; and, have different screened intervals. Each well in a well cluster is a typical monitoring well with a single casing and a short screened interval. A well cluster is shown on Figure 2.

Well clusters are used to provide vertical profiles of COC concentrations (within an aquifer or between aquifers) and to establish upward and downward groundwater flow directions (known as vertical hydraulic gradients).

Because the wells in a cluster are located close together, grouting of one well may impact the water quality (e.g., pH) of the other wells in a cluster. If the horizontal groundwater flow direction is known, the shallowest well in the cluster should be located upgradient of the deeper wells in the cluster, to minimize potential impacts on shallow groundwater quality due to grouting of the deeper wells.

Wells in a cluster should not have overlapping screened intervals. Overlapping screened intervals may facilitate cross-contamination via wells in the cluster when vertical gradients are present, a process called “stair-stepping” (Einarson 2006).

2.7.2.2 Nested Wells

Nested monitoring wells serve the same purposes as a well cluster. Instead of several individual wells located in close proximity, nested monitoring wells consist of two or more well casings with different screened intervals within the same borehole. To accommodate several well casings, a borehole with a larger diameter is required. Each screened interval is isolated from the others by annular seals (DWR 1991). Nested wells are shown on Figure 2.

Nested monitoring wells can be difficult to construct. For example, it is difficult to install several filter packs and several bentonite seals within a crowded annular space. A larger-diameter borehole may be necessary.

Leakage between zones may occur along the well casings as well as along the borehole. With nested wells, it is difficult to ensure that: water-bearing zones for each well casing are hydraulically isolated from one another; annular seals between each zone are effective; and, filter packs are properly installed.

Decommissioning by over-drilling may not be possible.

Therefore, DTSC discourages the use of nested monitoring wells at contaminated sites.

If nested wells are used, well alignment and plumbness are critical for successful installation of filter packs and annular seals. However, no commercially available spacers or centralizers are available and custom-made centralizers may make installation difficult (e.g., by obstructing tremie pipes) (Einarson 2006).

BESST Inc. developed a commercially available nested well system, which uses ZIST™ technology to isolate screened intervals.

2.7.2.3 Multi-Level Systems (MLSs)

Commercially available engineered MLSs include: Westbay MP®, Solinst Waterloo®, Solinst CMT®, and Water FLUTe™. Figures illustrating various multi-level systems, a detailed analysis, and a tabulated comparison of the systems are presented by Einarson (2006). A generic MLS is shown on Figure 2.

MLS costs (e.g., for materials, installation, and sampling) are usually greater than costs for conventional monitoring approaches. However, life cycle costs may decrease, mass removal may increase, and time frames for certification/completion may decrease, due to remedial optimization (e.g., targeting zones of high concentration or flux).

Generalized advantages and disadvantages of MLSs are listed below; however, these summaries may not apply to particular systems. Each system should be evaluated individually, based on performance requirements and site conditions. Consultation with MLS manufacturers is recommended.

Advantages of MLSs are:

- Multiple discrete intervals can be sampled in one borehole;
- MLSs can be used in consolidated and unconsolidated lithologies, including heterogeneous formations;
- Vertical profiles of hydraulic head can be measured;
- Vertical flow within the borehole is prevented;
- One pipe is placed in the borehole, simplifying well construction (e.g., compared to nested wells or cluster wells);
- The volume of purged water is low (compared to cluster wells), which decreases the cost for waste disposal;
- Remediation approaches (e.g., injection and extraction) can be targeted to zones of high contaminant concentration and/or flux, as identified by MLS sampling

data;
- Well permitting costs, which are usually determined on a per hole basis, may be reduced; and,
- Time-series monitoring of plumes at multiple depths along a transect can be conducted to: monitor source depletion, assess in situ remediation (including monitored natural attenuation), ensure sufficient amendments are delivered to targeted intervals, and estimate mass flux/discharge. (These objectives can also be realized using individual wells or well clusters.)

Disadvantages of MLSs include:

- Training is recommended for first-time installers and samplers of the systems;
- In open boreholes, care must be taken to prevent vertical flow (and cross-contamination) during MLS installation;
- MLSs may be difficult to install at depth and in fractured rock (e.g., due to deviation from plumbness);
- Water levels cannot be measured directly; however, pressure sensors can be used;
- Because of the narrow inside diameters (IDs) of sampling tubes, sampling and analysis options may be limited (e.g., sampling volumes may be low and special pumps with small outside diameters [ODs] must be used);
- Sampling ports may clog and systems may be difficult to develop;
- High concentrations in closely-spaced tubes can diffuse into adjacent tubes;
- Some MLSs may be treated with biocides (e.g., arsenicals) or may contain other compounds (e.g., 1,4-dioxane) which may leach into samples;
- MLS components may be incompatible with some remediation technologies (e.g., chemical oxidation and thermal approaches); and,
- Maintenance and decommissioning may be difficult.

In unconsolidated deposits, MLSs must be constructed inside a casing, which is withdrawn or pulled back as construction proceeds. Alternatively, MLSs can be installed inside steel or polyvinyl chloride (PVC) wells constructed with multiple well screens: this approach may facilitate more reliable decommissioning. Solinst CMT® and Water FLUTe™ can be installed using various drilling methods (e.g., wireline and dual-tube direct push methods). Pressure transducers to monitor water elevations, and other sensors, can be used with all MLSs.

MLS selection criteria are discussed in Kueper et al (2014). Recent advances in other topics, including measurement of mass flux/discharge (e.g., using passive flux meters, integral pumping tests, etc.), are also summarized in Kueper et al (2014).

3.0 MONITORING WELL DESIGN AND CONSTRUCTION

3.1 Borehole Design

Monitoring well planning should identify borehole integrity as a primary design criterion. The following factors should be considered in the borehole construction:

- Drilling method;
- Borehole diameter;
- Annular space;
- Borehole alignment;
- Total depth of the borehole;
- Selection of annular materials;
- Well development; and,
- Workplace safety.

The diameter of a monitoring well borehole should be sufficiently large to contain the well casing and provide an adequate annular space, as measured from the outside diameter of the casing to the borehole wall.

DWR's (1991) minimum annular space widths are 2 inches:

- between the casing and the borehole wall;
- between the well casing and the conductor casing; and,
- between the surface conductor casing and the borehole wall.

The minimum annular space should be increased as needed to allow clearance of equipment that may be installed in the annular space, such as pipes used to emplace sand or grout (aka tremie pipes) or sounding tubes (for measuring water, filter pack, or grout levels). Nielsen (2006) says that 2 inches to 3 inches should suffice for the width of an annular space.

To be compliant with DWR (1991) annular space requirements, the borehole diameter would need to be 4 inches greater than outside diameter (OD) of the well casing. Therefore for well casings with 2-inch and 4-inch ODs, the boreholes should have nominal diameters of 6 and 8 inches, respectively. However, because it is impractical to prepare site-specific standards covering every conceivable case, DWR (1991) allows deviation from these standards. For example, smaller annular spaces may be specified, as for direct push wells with pre-packed well screens (Major et al. 2009). Whenever the well design deviates from the DWR standards, the well designer (i.e., PG or PE) must ensure that the intent of the DWR standards has been met.

Annular spaces spanning more than 2 to 3 inches may result in an increase in the time required to develop a well because recovery time is directly proportional to volume

(Nielsen 2006). In low-permeability zones, where the time to recovery is significant, smaller annular space widths (hence lower volumes) are preferred. Also, as the annular space width increases, the potential for well casing damage from exothermic heating during grout curing also increases, especially for PVC wells. Unit costs for construction (e.g., for drilling and materials) increase as the annular space widths increase, as does the volume of waste for disposal.

In situations where precise screen locations are needed (e.g., for targeted remediation zones or for lithologic units in dipping or folded strata), borehole plumbness and alignment can become an important criterion for monitoring well screen installation. Borehole plumbness and alignment can be assessed with a borehole deviation survey, using a borehole dipmeter or a similar downhole tool. Fortunately, misalignment is usually not significant for monitoring well boreholes that are less than 200 feet deep; therefore, the additional cost for borehole deviation surveys is usually not justified. However, where precise geologic or hydrogeologic information is needed from boreholes significantly greater than 200 feet, borehole deviation surveys are recommended.

The depth of each monitoring well is determined by site-specific hydrogeologic conditions, the CSM, and the DQOs. For example, wells may be designed to monitor the water table, an entire water-bearing zone, or discrete zones of the aquifer (e.g., shallow, middle, and deep). Regardless of monitoring depth, the depth of completion of the monitoring well borehole should generally be within one foot of the bottom of the screened interval.

Sometimes boreholes are drilled to a depth greater than the final design depth of the monitoring well, either for exploratory purposes or by error. Boreholes that are not sealed below the final design depth (whether collapsed or left open) may create a vertical conduit for preferential flow (and contaminant migration). Also, when a well is constructed with a large open space or a large volume of filter pack below the well screen, purging and sampling may bring up a non-representative volume of water from below the screen. Therefore, boreholes should be backfilled with a low-permeability material (e.g., a neat cement-bentonite grout) to the design depth of the monitoring well. However, using cement materials to backfill boreholes may temporarily increase the pH of the groundwater, impacting contaminant concentrations and water quality parameters.

3.2 Site Stratigraphy

Stratigraphy refers to the geometric relationships between different soil, sediment, and rock layers (or strata). For example, site stratigraphy could include a description of a repeating sequence of sand, silt, and clay. By studying stratigraphic relationships, the depositional environment (e.g., fluvial sequence, alluvial fan, or colluvial deposit) and other site features (e.g. faults, flows, or fractures) can be interpreted.

Stratigraphy is an essential component of the CSM and is used for:

- Understanding the site's hydrogeology (e.g., preferential pathways, water-bearing zones, confining layers, and fault-controlled flow regimes) and geological history (based on fossils and other dating techniques);
- Designing site investigations consistent with the CSM (e.g., selecting optimum locations for monitoring wells);
- Identifying potential migration pathways for contaminants (e.g., sand lenses and buried stream beds); and,
- Prioritizing zones for targeted remediation (e.g., zones of high COC concentration or high flux).

Site stratigraphy is based on site-specific data from borehole cores, CPTs, and other tools (e.g., surface and borehole geophysics), as well as data from other sources (e.g., from nearby site investigations and from scientific literature on local hydrogeology).

Borehole cores should be logged for lithology (and, in some cases, petrology and pedology). Care should be taken to ensure every geologic formation, especially each confining layer, is represented in the boring log and that the nature of stratigraphic contacts is determined. Typically, clay layers are easier to identify during drilling than silty or sandy layers. Observations such as fining upwards sequences and unique lithologic compositions should be included on logs. Recommendations for drilling and logging are presented in *Drilling, Logging, and Sampling at Contaminated Sites* (CalEPA 2013).

Boreholes for monitoring wells should be continuously cored and logged. The extent of LNAPLs and other COCs with distinguishing characteristics such as odor, staining, color, and viscosity can be estimated using field observations during continuous coring. In suspected LNAPL and DNAPL source areas, field measurements of the continuous core can be collected with an organic vapor analyzer [OVA], photoionization detector [PID], and hydrophobic dye tests. These field measurements can be used to refine the CSM and to evaluate remedial options.

When continuous coring of every borehole is not feasible, selected boreholes should be continuously cored, to provide representative coverage of subsurface geology and areas of interest to the study. For boreholes that are not continuously cored, cores should be collected at all suspected changes in lithology. The screened interval (or open interval) of the well should be continuously cored. For drilling methods for which continuous coring is not feasible, soil behavior types (from CPTs) may be more practical for selecting screened intervals, provided that CPT results have been correlated with site lithology.

Physical characteristics of the screened interval, especially grain-size distribution, are fundamental for filter pack and well screen design and are useful for evaluating remedial options. At least one sample for physical analyses should be collected from the screened or open interval of the monitoring well. Chemical analyses of the sample from the screened interval will allow for cross-media comparisons of COCs (e.g., in groundwater, soil, and soil vapor). For example, an unsuspected soil source contributing to groundwater or soil vapor contamination may be identified. In complex geologic settings, borehole geophysical logging, surface geophysical surveys, and/or CPT surveys should be utilized to enhance understanding of the hydrogeology and to further develop the CSM. When planning such surveys, it is important to remember that drilling methods and well casings/screens will influence the selection of geophysical methods (e.g., electrical resistivity logging cannot be performed in cased wells). Recommendations for geophysical methods are presented in *Application of Borehole Geophysics at Hazardous Substance Release Sites* (CalEPA 2012b) and *Application of Surface Geophysics at Contaminated Sites* (CalEPA 2012c).

Stratigraphic cross-sections parallel and perpendicular to groundwater flow direction should be prepared and submitted in a report. The number and locations of the cross-sections should be sufficient to illustrate the geologic and hydrogeologic features that may influence contaminant transport. Cross-sections should be based on monitoring well boring logs and other soil boring logs collected during the site investigation. Information from other investigative technologies such as CPTs, MIPs, HPTs, and geophysical surveys should be incorporated into cross-sections. Three-D representations (e.g., of lithologic units or channel features) are also useful for illustrating and evaluating the CSM. Site stratigraphy on the cross-sections should be compared to regional stratigraphy.

3.3 Selection of Drilling Method

Monitoring wells can be installed using either traditional drilling methods or DP tools. Installation, alteration, destruction, or decommissioning of monitoring wells requires a C-57 Water Well Contractor's License (commonly referred to as a driller's license).

Drilling methods commonly used in hydrogeologic investigations are: hollow-stem auger, mud rotary, air rotary, percussion, rotasonic, and DP. Primary technical factors that influence the selection of well installation methods are: lithology, target depth, and the potential for cross-contamination. Other considerations include: artesian conditions, waste generation, access to water, noise, and space required for drilling operations.

Selection of drilling methods is outside the scope of this guidance. An overview of various drilling technologies is presented in *Guidelines for Planning and Implementing Groundwater Characterization of Hazardous Substance Release* Sites (CalEPA 2012d). Advantages and disadvantages of each method are presented in *Table 4-1 Summary of Drilling Methods* and *Table 4-2 Drilling Methods for Various Geological Settings*. Drilling methods are also discussed in *Drilling, Logging, and Sampling at Contaminated Sites* (CalEPA 2013), and in Aller et al. (1989), Sterrett (2007), and Roscoe Moss Company (1990), among others.

3.4 Well Casing Diameter

While casing outside diameters (ODs) are standardized by American National Standards Institute (ANSI) for casing less than 14 inches in diameter, variations in casing wall thickness cause casing IDs to vary. In ANSI-scheduled casing, casing wall thickness increases as the scheduling number increases for any given diameter of casing. For example, nominal 2-inch casing is a standard 2.375 inches OD; however, wall thicknesses vary from 0.065 inch for Schedule 5 to 0.218 inch for Schedule 80. This means that IDs for nominal 2-inch casing vary from 2.245 inches for Schedule 5 thin-walled casing (typical of stainless steel) to only 1.939 inches for Schedule 80 thick-walled casing (typical of PVC). Because Schedule 80 PVC is thicker than Schedule 40 PVC, using Schedule 80 PVC wells should extend the life of the monitoring system compared to Schedule 40 PVC.

A method of evaluating casing strength is by standard dimension ratios (SDRs). The SDR is the ratio of the casing wall thickness to the casing OD. The ratio is referenced to the internal pounds per square inch (psi) pressure rating such that all casings with a similar SDR will have a similar pressure rating. Where strength of casing is important, scheduling and SDR numbers provide a means for choosing casing. Strength characteristics are discussed in *4.0 Well Casing and Screen Materials*.

Although the diameter and thickness of the casing for a monitoring well depends on the purpose of the well, the casing size is generally selected to accommodate downhole equipment such as pumps and water quality meters. Additional casing diameter selection criteria include:

- Drilling or well installation method used;
- Depth of the well and associated strength requirements;
- Well development method;
- Purge water volume; and,
- Aquifer testing.

The quantity of waste requiring proper disposal (i.e., purged water, development water, and drill cuttings) increases as well diameter increases: waste disposal may be a significant cost consideration for the well designer. To minimize waste generation, 2-inch or 4-inch diameter wells should be used whenever practical (generally to depths less than 200 feet).

The time required for well recovery also increases with well diameter. In particular, in low permeability formations, where recovery time is naturally slow, the increased recovery time associated with larger diameter casing may be an additional design consideration.

Larger diameter wells may be necessary if: dedicated purging or sampling equipment is used; the well is screened in a deep formation; conductor casings are used; or, a nested well or MLS is to be constructed.

3.5 Casing Cleaning Requirements

Well casing and screen materials should be cleaned prior to installation to remove any coatings or manufacturing residues. Casing and screen materials should be certified-clean. Many drilling companies provide casing and screens which are certified clean by the supplier/manufacturer, and delivered to the site in individual sections wrapped in plastic and/or boxed.

If not certified as clean, all casing and screen materials should be washed with a mild non-phosphate detergent/potable water solution and rinsed with potable water. Hot pressurized water, such as in steam cleaning, should be used to remove organic solvents, oils, and lubricants from casing and screens composed of materials other than plastic. At sites where volatile organic contaminants may exist, cleaning of well casing and screen materials should include a final rinse with deionized water or non-chlorinated potable water. Cleaning procedures are further described in Aller et al. (1989).

Once cleaned, casings and screens should be stored in an area that is free of potential contaminants. Plastic sheeting can generally be used to cover the ground in the decontamination area to provide protection from contamination.

3.6 Coupling Procedures for Joining Casing

Only a limited number of methods are available for joining lengths of casing or for joining casing and screen together. The joining method depends on the type of casing and type of casing joint. For plastic casing, flush-joint, threaded flush-joint, plain bell-end, and square-end casing joints are typical. For metallic casing, threaded flush-joint, bell-end, and plain square-end casing joints are typical.

Incompatible threading between casing and screen may cause delays in installation and decoupling during installation. Because threading may vary with manufacturer and may even vary with production runs, care should be exercised when ordering threaded casing and screen.

3.6.1 Metallic Casing Joining

There are generally two options available for joining metallic well casings: 1) welding via application of heat and 2) threaded joints. Both methods produce a casing string with a relatively smooth ID and OD. With welding, it is possible to produce joints that are as strong as—or stronger than—the casing, thereby enhancing the tensile strength of the casing string. The disadvantages of welding include: 1) greater assembly time; 2) difficulty in properly welding casing in the vertical position; 3) enhancement of corrosion potential in the vicinity of the weld (see Section 4.3.2); and, 4) danger of ignition of potentially explosive gases that may be present.

Because of the disadvantages of welding, threaded joints are more commonly used with metallic casing and screen. Threaded joints provide inexpensive, fast, and convenient connections and greatly reduce potential problems with chemical resistance or interference (due to corrosion) and explosive potential. Using O-rings (i.e., nitrile, ethylene propylene, or Viton) between sections or wrapping the male threads with fluoropolymer (e.g., Teflon®) tape prior to joining sections improves the water-tightness of the joint. One disadvantage to using threaded joints is that the tensile strength of the casing string is reduced to approximately 70 percent of the casing strength. This reduction in strength does not usually pose a problem because strength requirements for small diameter wells (such as typical monitoring wells) are not critical and because metallic casing has a high initial tensile strength.

3.6.2 Thermoplastic and Fluoropolymer Casing Joining

The most common method of mechanical joining of thermoplastic and fluoropolymer casing and screen is by threaded connections. Molded and machined threads are available in a variety of thread configurations including: acme, buttress, standard pipe thread, and square threads. Because most manufacturers have their own thread type, threaded casing may not be compatible between manufacturers. If the threads do not match and a joint is made, the joint can fail or leak either during or after casing installation.

Joints should create a smooth and uniform ID and OD in monitoring well installations. Casings with threads machined or molded directly onto the pipe (without use of larger-diameter couplings) provide flush joints between both IDs and ODs. Because the annular space is frequently minimal, casings that do not use couplings are best suited for use in monitoring well construction. An inconsistent ID causes problems when tight-fitting downhole equipment is used (e.g., development tools, and sampling or purging devices). An uneven OD casing creates problems with filter pack and annular seal installation. Also, an uneven OD may promote water migration at the casing/seal interface to a greater degree than is experienced with uniform OD casing (Morrison 1984).

Because all joints in a monitoring well casing should be watertight, the extent to which the joints are tightened should comply with recommendations of the manufacturer. Over-tightening casing joints can lead to structural failure of the joint (ASTM 2005; National Water Well Association and Plastic Pipe Institute 1981). Where threaded joints are used, and as allowed by manufacturer’s specifications, fluoropolymer tape may be wrapped around the threads prior to joining male and female sections to maximize the water-tightness of the joint, and an O-ring may be added for extra security.

Solvent cementing of thermoplastic pipe should not be used in the construction of groundwater monitoring wells. In solvent cementing, a solvent primer is generally used to clean the two pieces of casing to be joined and a solvent cement is then spread over the cleaned surface areas. The two sections are assembled while the cement is wet. This allows the active solvent agent(s) to penetrate and soften the two casing surfaces that are joined. As the cement cures, the two pieces of casing are fused together; a residue of chemicals from the solvent cement remains at the joint. The cements used in solvent welding, which are themselves organic chemicals, have been show to adversely affect the integrity of groundwater samples (Aller et al. 1989). General information is provided in ASTM (2005).

3.7 Well Intake Design

The well intake includes: the screened interval, the primary filter pack, the secondary filter pack (i.e., the fine sand transition zone above the primary filter pack), the well screen, and the silt trap (Figure 1). The intakes of monitoring wells should be designed and constructed to: 1) accurately sample the water-bearing zone which the well is intended to monitor; 2) reduce turbidity by minimizing the passage of formation materials into the well; and, 3) ensure sufficient structural integrity to prevent the collapse of the intake structure.

Well efficiency, which is a critical design consideration for production wells and for extraction wells, is not usually a controlling factor in monitoring well design and is not discussed further, except to note that well efficiency can be improved by increasing the open area of the well screen (e.g., by specifying a wire-wrapped screen).

3.8 Well Screen

The goal of a properly completed monitoring well is to provide low turbidity water that is representative of groundwater quality in the vicinity of the well. Monitoring wells completed in unconsolidated sediments require screens, to prevent migration of formation materials and filter pack materials into the well casing. The portion of the well casing that is screened (Figure 1) is referred to as the screened interval.

Wells constructed in indurated rock may not need to be screened, because the formation material (i.e., hard rock) will not migrate into the well casing.

3.8.1 Screen Length

The selection of screen length usually depends on the objective of the well. Piezometers, for example, are generally completed using short screen lengths (2 feet or less), as are wells where only a discrete flow path is monitored, such as thin gravel layers that are interbedded with clays. To avoid dilution of COC concentrations, well screens should be kept to the smallest length possible for intercepting a contaminant plume, especially in a high-yielding aquifer zone. The screen length should generally not exceed 10 feet. However, if construction of a water table well is the objective, then a longer screen spanning the fluctuating water table is appropriate. Water table fluctuations may be due to seasonal or tidal loading, or due to nearby recharging or pumping wells. Water table wells may also be needed to evaluate the presence of LNAPLs or the extent of the LNAPL smear zone. A detailed discussion of screen lengths is provided in *2.7.1.2 Long-Screened Wells*.

Screen lengths that create a conduit for contaminant transport across hydraulically-separated geologic units or between zones of high concentrations of COCs and low COC concentrations should not be employed.

3.8.2 Screen Slot Size

Well screen slot size should be selected to retain at least 90% of the filter pack material when designing a well with an artificial filter pack, or retain a minimum of 50% of the formation material in naturally-packed wells (as determined from particle-size analyses), unless it is demonstrated that turbidity-free water (less than 5 nephelometric turbidity units [NTUs]) can be obtained using a larger slot size. Although these retention percentages may be higher than are required in production wells, the low withdrawal rates and the infrequent use of a monitoring well sanction higher retention percentages.

Slot sizes of 10 and 20 (i.e., 0.010 and 0.020 inch) are commonly used. However, site-specific designs should be developed. For example, slot sizes of 10 and 20 may not be suitable for fine-grained materials, because 90% of fine-grained materials may exceed 0.10 or 0.20 inch, and, consequently, well water may be turbid. Nielsen (2006) summarizes options for designing slot sizes and filter packs in fine-grained materials, including the use of pre-packed or sleeved well screens with slot sizes as low as 4 (i.e., 0.004 inch in a wire-wrapped screen) with filter packs of very fine sand or silica flour. (Pre-packed and sleeved well screens are discussed in Section 3.8.3.)

In general, filtering a sample subsequent to its collection is not the desired solution for dealing with turbidity in an improperly designed well. Proper well screen and filter pack selection should be followed and proper development and periodic well maintenance should also be conducted. Turbidity is discussed further in Section 3.16.1.

Well screens should be factory-slotted screens or wire-wrapped screens. The purposes of the well should guide screen selection. For example, if higher flow is a DQO for the well, V-slotted screens might be selected over continuous wire-wrapped screens. Manually-slotted screens are not acceptable.

3.8.3 Pre-Packed (and Sleeved) Well Screens

A pre-packed well screen is an assemblage that consists of: an internal well screen (e.g., a continuously-slotted screen); an external well screen (e.g., a continuously-slotted screen, or a mesh sleeve); and a filter pack in the space between the internal and external screens (or between the internal screen and the mesh sleeve). If a mesh sleeve is used (generally made of stainless steel [SS]), the assemblage may be referred to as sleeved well screen.

Pre-packed or sleeved well screens are especially useful for obtaining low-turbidity samples (e.g., in fine-grained formations like clay or silt) or for installing a filter pack in difficult conditions (e.g., in heaving silt or sand).

Specifications for slot size and filter pack (i.e., to ensure low turbidity) and chemical compatibility (e.g., to prevent sorption, leaching, or biofouling) are critical design parameters. Pre-packed well screens are commercially available in a variety of sizes and can be built to specifications. Pre-pack well screens can be delivered intact or assembled in the field and are often installed using direct push methods (ASTM 2010b).

Because purged water volume is decreased when pre-packed or sleeved well screens are used, investigation-derived waste (IDW) may be reduced. Soil IDW will also be reduced if DP methods are used. Installation may be quicker and more efficient, resulting in lower costs.

Because even and accurate placement of filter pack material across the screened interval is ensured, without bridging or particle-size segregation, a smaller width of filter pack may be acceptable. For example, for direct push wells, filter packs of less than 0.5-inch have been successfully installed using pre-packed well screens (Nielsen 2006). Theoretically, a filter pack of only 2 or 3 grain diameters is necessary to contain and control formation materials (Driscoll 1986, Nielsen 2006).

3.8.4 Bottom Plugs

Bottom plugs should be used on monitoring wells to prevent heaving soil from entering the bottom of the casing during well development and to prevent the creation of voids at the bottom of the casing during purging and development.

Damage to the bottom plug during installation or subsequent activities (e.g., by dropping tools down the well) may compromise the integrity of a well, to the extent that the well may need to be replaced. To prevent this unfortunate occurrence, specification of higher strength bottom plugs (e.g., Schedule 80 plugs on a Schedule 40 well casing) is an inexpensive and effective option.

3.8.5 Silt Traps

Silt traps are sections of blank casing (with bottom plugs) installed below the screened interval. Generally, silt traps are 6 to 12 inches long. Fine-grained particles settled into the silt trap (instead of the screened interval) can be removed by bailing or pumping. By temporarily sequestering fine-grained particles, silt traps may extend the useful life of a well and minimize well maintenance, especially for wells installed in clay and silt units. Silt traps can be used to detect or collect DNAPLs. In such a case, silt traps would be useful in sand and gravel formations as well as in silt and clay formations.

3.9 Filter Packs

The material that fills the annular space between the screened interval and the borehole wall is referred to as the filter pack (Figure 1). The filter pack should extend at least two feet above the top of the well screen. One to two feet of transition sand is placed over the filter pack. Greater thickness of filter pack and transition sand are recommended by Nielsen (2006). The filter pack adjacent to the well screen is sometimes referred to as the primary filter pack and the overlying transition sand is described as the secondary filter pack.
The entire length of the annular space that is filled with permeable filter pack material or transition sand is effectively the monitored zone. Therefore, if the filter pack and transition sand extends from the screened interval into an overlying water-bearing zone, a conduit for the transport of contaminants may be created between the two zones: this situation should be avoided.

3.9.1 Filter Pack (Primary Filter Pack)

The purpose of the filter pack is to minimize the passage of formation materials into the well. Most wells require artificial (i.e., designed and constructed) filter packs and well screens, which are installed by the driller. However, natural filter packs may work well when the adjacent formation materials are well sorted (i.e., of mostly uniform size) and relatively coarse-grained (e.g., beach sand). A natural filter pack is formed when the adjacent formation collapses around the well screen. Wells with natural filter packs are also referred to as direct-contact, exposed screen, or no-pack wells (e.g., DP no-pack wells). Wells in hard rock often do not require screens, and thus do not require filter packs.

An artificial filter pack is appropriate in most geologic settings. In particular, an artificial filter pack should be used when the natural formation:

- Is poorly sorted, thin-bedded, or highly fractured;
- Is a uniform fine sand, silt, or clay;
- Is a poorly cemented sandstone;

- Includes shale or coal that will act as a constant source of turbidity to groundwater samples;
- Comprises highly stratified geologic materials of widely-varying grain sizes; or,
- Contains large solution channels.

An artificial filter pack may also be appropriate when a long screened interval is used or when the diameter of the borehole is significantly greater than the diameter of the well screen.

The filter pack and transition sand should completely fill the annular space between the well screen and the borehole wall. Filter pack widths is generally about 2 inches (consistent with widths for annular sealant). However, filter packs with an annular space width of 0.5 inches have been successfully installed in direct push wells with pre-packed well screens (Nielsen 2006). Theoretically, a filter pack of only 2 or 3 grain diameters is necessary to contain and control formation materials (Nielsen 2006).

Filter pack material should be chemically inert and durable. Ideally, filter packs would be made from industrial grade quartz sand (Barcelona et al. 1985a). Generally, filter packs are built with commercially available sand that has been washed and kiln-dried. However, if the source of the sand is suspect or questionable, the sand should be analyzed for cation exchange capacity, VOCs, and other COCs (e.g., metals, salts) which may interact with COCs in the soil or groundwater—or, confound analytical results. Commercially available pea gravel may be acceptable for use in gravel aquifers; however, because the filter pack should be chemically inert, the pea gravel itself should not be chemically active or coated with a chemically-active metal oxide. Filters constructed from fabric should not be used, as they tend to plug and may be chemically reactive. Nielsen (2006) provides a comprehensive discussion of the purpose and selection of filter pack materials.

Various methods for selecting the size of filter pack materials exist. The quote by Aller et al. 1989, provided below, summarizes various approaches.

> "Although design techniques vary, all use the filter pack ratio to establish size differential between the formation materials and filter pack materials. Generally this ratio refers to either the average (50 percent retained) grain size of the formation material or the 70 percent retained size of the formation material. For example, Walker (1974) and Barcelona et al. (1985a [1985b in this document]) recommend using a uniform filter pack grain size that is 3 to 5 times the 50 percent retained size of the formation materials. Driscoll (1986) recommends a more conservative approach by suggesting that for fine-grained formations, the 50 percent retained size of the finest formation sample be multiplied by a factor of 2 to exclude the entrance of fine silts, sands, and clays into the monitoring well. The United States Environmental Protection Agency (1975) recommends that filter pack grain size be selected by multiplying the 70 percent retained grain size of the formation materials by a factor between 4 and 6. A factor of 4 is used if the formation is fine and uniform; a factor of 6 is used if the formation is coarser and non-uniform. In both cases, the uniformity coefficient of the filter

> pack materials should not exceed 2.5 and the gradation of the filter material should form a smooth and gradual size distribution when plotted. The actual filter pack used should fall within the area defined by these two curves. According to Williams (1981), in uniform formation materials, either approach to filter pack material sizing will provide similar results; however in coarse, poorly sorted formation materials, the average grain size method may be misleading and should be used with discretion."

A well design specification (WDS) software package, recently developed by Kramer and Farrar, allows for selection of filter packs based on CPT soil type characteristics (Major et al. 2009).

The geologist should specify the method of filter pack selection for each well. However, in areas where the properties of local formations are well-known, geologists may specify suitable filter pack materials, without ordering particle size analyses for each well on a site. In such as case, information about the local formations (preferably site-specific information) should be included in the work plan.

Prior to filter pack installation, the volume of filter pack material should be estimated and recorded. During installation, a weighted tape should be used as a sounding device, to measure the height of the filter pack. Field measurements of the filter pack material emplaced in the well should be continually compared to estimated volumes. Any discrepancies should be documented, explained, and corrected prior to emplacement of the bentonite seal to ensure that bridging or particle-size segregation has not occurred. Bridging occurs when particles clump together, due to: obstructions (like centralizers), narrow annular spaces, borehole collapse, rapid pouring, or segregation of particles during transport down the annular space. Voids in the filter pack (or annular seal) below the bridged material threaten the well integrity (and increase turbidity). Filter pack volumes that are less than anticipated (i.e., less than design volumes) may indicate that bridging has occurred. In this case, the weighted tape (or a tamping rod) should be used to break up bridges and help to settle the filter pack. Alternatively, if field measurements of filter pack volumes are larger than calculated volumes, significant voids may exist in the subsurface (e.g., in formation materials) or utilities corridors (or tanks) may have been breached.

Filter pack material should be tremied into the annular space, to prevent bridging and to minimize grain-size segregation (DWR 1991). Many local ordinances prohibit free fall of filter pack material for wells that are deeper than 20 feet.

In shallow wells, gently vibrating or surging the well after placing the filter pack may facilitate settling of the filter pack and break up any bridging, prior to grout emplacement.

In deep wells, the filter pack may not settle when initially installed. The filter pack may settle later on, as the filter pack particles rearrange themselves as bentonite, annular, and surface seals are placed on top of the filter pack—or, during well development. Delayed settlement of the filter pack may result in voids in the filter pack or in penetration of grout into the well screen. Consequently, filter packs may need to be installed as high as five feet above the screened interval in monitoring wells that are greater than 200 feet and allowed to settle prior to installing the bentonite seal. Careful and gentle surging after placing the filter pack (but prior to placing the bentonite seal) can help to settle the filter pack. Surging is complete when the depth to filter pack stabilizes.

Special techniques (e.g., use of pre-packed well screens or applying additional hydraulic head) may be needed to install filter packs and other well components in heaving sands and silts and in flowing artesian conditions.

3.9.2 Transition Sand (Secondary Filter Pack)

The transition sand comprises one to two feet of chemically inert fine sand, emplaced directly above the filter pack (Figure 1). The transition sand prevents the leakage or seepage of the overlying bentonite seal into the underlying filter pack. Nielsen (2006) provides guidance on the design of transition sand.

Depending on site conditions (e.g., the grain-size distribution of filter pack and formation, the height of the annular seal), an overlying bentonite seal of bentonite chips or pellets may suffice: that is, the transition sand may not be necessary (Nielsen 2006). However, because of the time required for bentonite chips or pellets to properly hydrate prior to placement of the annular seal, installation of a transition sand might be specified as a time-saving measure.

3.10 Well Casing Installation

Casing lengths may not be exactly as described. Therefore, prior to casing installation, it is good practice to measure well casing lengths in the field to confirm that the depth of the well screen is consistent with the designed depth of the well screen. The cumulative impact of incorrect casing lengths increases as well depth increases.

3.10.1 Centralizers

Centralizers ensure that the well casing is centered in the borehole during installation of the filter pack, transition seal, and annular seal (Figure 1) so that the required annular space widths are achieved. For example, in deep boreholes, casings have a tendency to bow, and may even contact the borehole wall: centralizers prevent such bowing.

If the casing is not centralized and the well casing contacts the borehole wall, the integrity of the annular sealant will be compromised. Bonding will not occur between the grout and the well casing and between the grout and the borehole wall, potentially resulting in cross-contamination.

A straight well casing is necessary for pumps, sampling tools, and other sensors to be deployed within the finished well.

Centralizers (either bowspring or rigid, usually made of PVC or stainless steel) are installed within the annular space at 10 to 20 foot intervals above the well screen. Centralizers may also be specified within the filter pack if the well screen is long. Centralizers may not be necessary if the well is shallow or if the well is installed using a hollow-stem auger or another drilling method that centers the casing in the borehole.

3.10.2 Buoyancy

Local hydrogeological information should be reviewed during well design and the potential for buoyancy identified, so that well design and installation can take buoyancy forces into account, and field emergencies can be averted. Buoyancy may be a consideration for wells screened: significantly below the water table, in artesian conditions, or in heaving sands or silts.

To counteract buoyancy (from water pressure or heaving sands), the well casing may need to be weighted (e.g., by hydraulic rams on the drill rig) or the casing may need to be filled with water. If water is added to the well, the volume of water added the well should be measured and all water added to the well should be removed following well installation. Water from a known and acceptable source should be used. Otherwise, water should be analyzed for water quality parameters and COCs prior to being added to the well.

For wells constructed using hollow stem auger drilling, a plug at the bottom of the well string may be used to keep water and heaving sands out of the drill string while setting the well. The plug should be made of environmentally inert materials. Such inert plugs are commercially available from well supply stores.

Care must be taken to not break plastic well casings or damage well screens when restraining them against buoyancy forces.

3.11 Sealing the Annular Space

The space between the monitoring well casing and the wall of the borehole is referred to as the annular space (or well annulus). The annular space is filled sequentially from the bottom to the top with: filter pack, transition sand, bentonite seal, annular seal, and surface seal (Figure 1). The bentonite seal, the annular seal, and the surface seal are discussed in this section. The filter pack and the transition sand were discussed in the previous section.

The bentonite seal, the annular seal, and the surface seal prevent the well annulus from serving as a vertical conduit for contaminant transport between the surface and the subsurface—and between zones within the well. Exchange of groundwater between zones of different water quality (e.g., between zones of varying salt content) is also prevented. The annular seal also precludes migration of vapors through the annulus.

Nominal lengths for filter pack (extending 2 feet above screened interval), transition sand (1 to 2 feet), bentonite seal (minimum of 2 feet), annular seal, and surface seal (extending below the frost zone) are discussed in this document. However, for a water-table well, where the groundwater is close to the ground surface, thicknesses of annular materials will need to be adjusted to accommodate the shallow depth of groundwater.

3.11.1 Bentonite Seal

The bentonite seal[1] prevents leakage or seepage of the overlying annular seal into the filter pack and into the screened interval of the well casing. The bentonite seal consists of a minimum of two feet of sealant material, usually bentonite, installed above the transition sand. In deep wells, the bentonite seal may be up to 5 feet long.

Bentonite is a naturally-occurring expanding montmorillonite clay that is processed into various forms (e.g., grains, pellets, chips, or slurry). Bentonite can be placed in a dry form or as a slurry (DWR 1991). Fine-grain forms of bentonite, such as grains and powder, are usually employed if the bentonite seal is above the groundwater water level (i.e., in the unsaturated zone). Bentonite slurry or coarse forms of bentonite, such as pellets and chips, are often used if the bentonite seal is below the groundwater water level (i.e., in the saturated zone) (DWR 1991).

In shallow wells (less than about thirty feet deep), bentonite pellets or chips may be dropped down the annulus (DWR 1991). However, dropping bentonite pellets or chips down the annulus may cause bridging in the annular space due to premature hydration of the bentonite, resulting in voids below the bridged material. Delayed time-release pellets (aka coated pellets) may be used to address this issue. A tamping device should be used to prevent bridging from occurring in shallow wells. Gently vibrating the well after dropping or tremieing the bentonite may also release bridged material.

Dry bentonite pellets or chips may be placed directly into the annular space, if a short section of annular space (up to 10 feet in length) is to be sealed (DWR 1991).

Tremieing pellets or chips may be problematic, because the pellets or chips may bridge inside the tremie pipe, clogging the pipe. The potential for bridging and void formation increases with the depth of the well, if dry bentonite is either dropped or tremied down the well annulus. Therefore, to avoid bridging and void formation, bentonite slurries are

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1 The annular material referred to as the bentonite seal in this document is referred to as the transition seal in DWR (1991). The fact that the word “transition” has been used in two different ways may cause some confusion. Moreover, an additional possible source of confusion arises from the statement in DWR (1991) that fine sand is sometimes used as the transition seal (i.e., in place of bentonite). If fine sand is used in place of bentonite, the work plan for well installation should demonstrate (e.g., by grain size comparisons) that the bentonite seal is not needed based on site-specific information.

often used. The slurry should be tremied around the well casing so that the slurry is evenly distributed.

Water should be added to bentonite at a ratio of one gallon of water per two pounds of bentonite (DWR 1991): more water may be needed if additives are used. Nielsen (2006) recommends placing the bentonite seal in 2-inch to 3-inch lifts with hydration between each lift. Water added to sealing materials should be compatible with the sealing material and free of contaminants. Generally, added water should be of drinking water quality. In some cases, non-potable water can be used for cement-based sealing materials, provided that the chloride content is less than 2,000 milligrams per liter (mg/L) and the sulfate content is less than 1,500 mg/L (DWR 1991).

The bentonite seal should be allowed to hydrate, set, or cure in conformance with the manufacturer's specifications prior to installing the overlying annular seal. The time required for the bentonite seal to hydrate, set, or cure will differ with the materials used and with the specific hydrogeological conditions encountered.   For example, it takes at least 1 to 2 hours for bentonite pellets or chips to hydrate sufficiently to hold up a column of grout (Nielsen 2006). However, 48 to 72 hours may be necessary for the seal to achieve a hydraulic conductivity of $1x10^{-7}$ centimeters per second (cm/sec): the hydraulic conductivity may decrease even further with extended wait times (Nielsen 2006). Local ordinances may specify wait times.

3.11.2 Annular (or Grout) Seal

The annular seal is installed on top of the bentonite seal and extends vertically up the well annulus between the well casing and the borehole to within a few feet of the ground surface (Figure 1). In no case should the top of the annular seal be more than four feet below the ground surface (DWR 1991). The surface seal is installed on top of the annular seal.

Expanding or non-shrinking formulations are necessary to ensure effective annular seals and surface seals.

Neat cement, sand cement, and bentonite are commonly used as annular sealants in groundwater monitoring wells. A general term used for annular sealants is grout. Grout is a mixture of water and an insoluble solid material which is used to fill void spaces. Annular sealant compositions are described in DWR (1991). For example, neat cement made with Type II Portland cement contains one 94-pound sack of cement and 5 to 6 gallons of clean water. Additional water may be required if additives are used (e.g., accelerators or retardants). Depending on site-specific conditions and on the well design and installation method, other annular sealants may be appropriate (e.g., shrinkage-compensated cement grout).

The hydraulic conductivity of the annular sealant should be one to two orders of magnitude lower than the least permeable part of the geologic formation in contact with the well.

The estimated volume of annular sealant should be calculated and recorded before construction, and the actual volume used in the field should be determined and recorded during well construction. Any discrepancies between the calculated volumes and the actual volumes should be explained and corrected as the well is being installed.

Prior to installing the annular seal, all loose cuttings and other obstructions should be removed from the annular space (DWR 1991).

Annular sealants should be tremied from the bottom-up, in one continuous operation. However, for wells more than 100 feet deep, the hydrostatic pressure of the annular seal (i.e., the weight of the overlying column of grout) may compromise the integrity of the underlying bentonite seal, resulting in leakage of the grout into the filter pack or into the well. In such cases, the deepest portion of the seal should be installed first and allowed to set. This initial annular seal should be no longer than 10 feet (DWR 1991). The remainder of the annular seal should be installed in one continuous pour.

The bottom of the tremie pipe should be kept submerged and should be equipped with a side discharge deflector to prevent the slurry from jetting a hole through the filter pack. Aller et al. (1989) provide detailed discussions of the proper placement of sealants into the annular space.

Dry bentonite pellets or chips may be placed directly into the annular space under water, where a short section of annular space, up to 10 feet in length, is to be sealed (DWR 1991).

If cement is used as an annular sealant, the cement type should be specified (e.g., Portland cement Types I through V) and be consistent with *Standard Specification for Portland Cement* (ASTM 2001a). Cement types have properties that have been developed for specific applications and environments. For example: Type I is a general purpose construction cement that should *not* be used in contact with soil and groundwater; Type II is a general purpose cement, for use in contact with groundwater and soils; Type III has increased early compressive strength but decreased ultimate strength; Type IV has a low heat of hydration, suitable for permafrost; Type V cement has high sulfate resistance, for use in alkali soils and in high sulfate groundwater (e.g., marine environments); and, Types Ia, IIa, and IIIa have an air-entraining agent which inhibits freezing.

Cement composition should be compatible with the soil and groundwater in the environment and should be evaluated to ensure absence of COCs (e.g., hexavalent chromium, sulfates). Chemical additives that may affect groundwater quality should not be used. Cement additives (e.g., accelerators and retardants) should meet the requirements of ASTM (2002). Similarly, concrete (which is comprised of cement plus aggregates like gravel) should be consistent with ASTM (2001b). The ratio of cement to water (based primarily on particle size) varies with cement type and additives.

The selection of cement should take into account: the chemical composition of the groundwater and soil; the heat of hydration during curing; strength requirements during construction and development; the time required to meet the desired strength; and, potential difficulties during decommissioning. For example: Portland cement may be incompatible with corrosive soils the heat of hydration of some cements may soften PVC casing; and, because of the strength requirements of deeper wells, thicker-walled PVC casing may be specified.
Minimum wait times for Portland cement are provided in DWR (1991) (e.g., 24 hours for Types I and II). Allowable setting times may be reduced or lengthened by the use of accelerators or retardants. More time is required for cement-based seals to cure to higher strengths, if subsequent construction or development operations may subject the well to higher stress (DWR 1991).

Bentonite is available in several compositions, primarily sodium bentonite and calcium bentonite. Sodium bentonite is usually acceptable for use as the bentonite seal or as a component of the annular sealant. However, if sodium bentonite is incompatible with either the natural formation or the COCs, other industrial-grade clays can be used. For example, calcium bentonite may be more appropriate in calcareous sediments and soils because of its reduced cation exchange capacity. The sealing properties of clays may be adversely affected by high concentrations of chlorine salts, acids, alcohols, ketones, and other polar compounds. If high concentrations of these materials are expected, alternative sealants should be considered.

Bentonite is an expansive clay which swells upon contact with water: this expansive property is essential for effective sealing. Therefore, because soil moisture in the unsaturated zone is not sufficient to keep bentonite fully hydrated, bentonite is not recommended as an annular sealant in arid regions and in the unsaturated zone (DWR 1991, Nielsen 2006). Moreover, bentonite may not rehydrate once it is desiccated (Olafsen Lackey et al. 2009).

When the annular sealant must be installed in the unsaturated zone, neat cement or shrinkage compensating cement (SCC) may be used for the annular sealant.   The formulation of the annular sealant should be compatible with site-specific climate and hydrogeology (Olafsen Lackey et al. 2009).

Calcium bentonite grout mixtures should not be used in the unsaturated zone because calcium ions (Ca^{++}) and hydroxide ions (OH^-) in the cement can cause flocculation of the clay, reducing its ability to swell. Similarly, in a saturated zone with high total dissolved solids (TDS, greater than 5000 ppm) or high chloride content, bentonite may flocculate, and the integrity of the well may be compromised (Nielsen 2006).

Bentonite improves the flow properties of cement grout, reduces shrinkage, and decreases the heat of hydration. However, bentonite also weakens the cement mixture, reducing its compressive strength. When compressive strength is a factor in well design, an alternate solution for shrinkage control is to use shrinkage-compensating additives components (ASTM 2001b and ASTM 2002). However, the high heat of hydration of these components should be taken into account when these materials are used in cement mixtures.

In areas where freezing is likely, the top of the annular seal may be below the frost line (but not more than 4 feet below the ground surface). In this case, the top of the annular seal should be within a watertight subsurface vault that encloses the top of the well casing.
Formation water and soil cuttings from the borehole wall will be displaced up the borehole when the annular space is filled with sealant. Waste water and other waste materials from well installation should be captured and handled appropriately: it should not be released to the ground surface. For example, a gooseneck “T” pipe can be fixed onto the top of the casing. Displaced water will then be directed through the gooseneck to a trough or other waste container. The work plan for well installation should describe how wastes will be characterized, handled, stored, and disposed.

3.11.3 Surface Seal

The surface seal (also known as a sanitary seal) is installed on top of the annular seal and extends vertically up the well annulus between the well casing and the borehole to the ground surface (Figure 1). The composition of the surface seal is generally an expanding cement or concrete (ASTM 2001b), which should be emplaced in a continuous pour. The composition of the surface seal may be identical to the composition of the annular seal (e.g., in shallow wells): in such a case, the surface seal may be a continuation of the annular seal.

For above-ground surface completions, the surface seal should form an apron (or base) around the protective casing. The well apron should: extend at least 2 feet laterally from the protective casing in all directions; be at least 4 inches thick; and, slope away from the protective casing (DWR 1991). The well apron should be placed in a continuous pour with the surface seal. Or, if the composition of the well apron is different from the surface seal, the apron should be placed on the surface seal before the surface seal has set (DWR 1991).

For flush-to-ground completions, the vault should form a watertight and structurally-sound connection with the annular seal and should extend from the top of the annular seal to at least the ground surface. The vault should be installed on top of the annular seal before the annular seal sets—or, before it is fully hydrated (if a bentonite-based sealing material is used) (DWR 1991).

Cement used for the surface seal and well apron should be resistant to cracking due to freezing and drying. In cold climates, air-entrained cement is generally preferred (Nielsen 2006).

In cold climates, the lower end of the surface seal should extend below the frost line (but not more than four feet below the ground surface) to prevent damage from frost heaving (DWR 1991)—and, the well apron should not extend beyond the borehole (Nielsen 2006).

Local ordinances should be consulted for specific surface/sanitary seal requirements that reflect local environmental conditions (e.g., freezing, flooding, and aridity), as well as local hydrogeology.

3.11.4 The Nebraska Grout Study

It has long been recognized that vertical conduits may be created between the well casing and the annular seal due to:

- Shrinkage during curing of the annular sealant;
- Poor bonding between the casing and the sealant;
- Bridging;
- Loss of grout into the formation; and,
- Temperature changes (Aller et al 1989).

The Nebraska Grout Task Force (NGTF) evaluated in situ grouts. Bentonite grouts with 20% solids are required to be used as annular seals for water wells in Nebraska's regulations (Olafsen Lackey et al. 2009). In initial studies, three bentonite slurry grouts (less than 20% solids, 20% solids, and greater than 20% solids) were tested. In later studies, additional mixtures were evaluated. Research sites had varied geology (i.e., glacial, alluvial) and climate (i.e., humid, arid). Based on the results of the studies, revisions to Nebraska's requirements may be proposed and other states may follow suit. Future field work may address ambiguities, conflicting results, and unresolved issues of the NGTF studies. Careful attention to future studies and to regulatory revisions is recommended.

Field work included: installation of wells, water level measurements, video surveys, and dye tests. Because the wells were installed with clear casings, direct observation of grout performance could be observed (and video-recorded) above the water table.

Below the water table, in general, bentonite chips performed as expected when hydrated and did re-hydrate. However, proper placement in boreholes was time-intensive and difficult in deep wells with narrow annular spaces.

Above the water table (i.e., in the unsaturated zone), annular seals pulled away from casings, and multiple voids and cracks developed. Vertical migration was patently observed during dye tests. Desiccated grout did not re-hydrate. Bentonite chips did re-hydrate.

Cement grouts cracked above and below the water table and did not bond to PVC pipe: micro-cracks were observed around the annulus and elsewhere. Sand-cement slurries provided structural stability and performed better than other cement-based slurries (above and below the water table) at some locations.

Infiltration of neat cement through the bentonite seal into the filter pack was observed at some locations, perhaps due to incomplete hydration of the bentonite seal. Placing two feet of fine sand between the bentonite seal and the annular seal was recommended by NGTF's contractors to prevent infiltration of neat cement through the bentonite transition seal.

The NGTF studies indicated that:

- There is no perfect grout that can be used successfully in all situations;
- Grout mixtures should be specified for each site condition (i.e., saturated/unsaturated, consolidated/unconsolidated, and sand/gravel);
- Different grouting approaches may need to be used in the same borehole; therefore, more detail should be recorded on the boring logs, especially in the unsaturated zone;
- Bentonite slurry grouts are sensitive to conditions in the unsaturated zone, especially to moisture content and particle size, and do not re-hydrate;
- High water content slurries (as used in DP methods) were ineffective above and below the water table; and,
- An increased percentage of solids (e.g., sand) in bentonite slurries may help to optimize performance of annular seals.

NGTF results regarding geothermal wells (I.e., closed-loop heat pump wells) are not summarized in this document.

3.12 Surface Completion

Monitoring wells are commonly completed at the surface in one of two ways: as above-ground completions or as flush-to-ground completions. The purposes of both types of completion are: to prevent infiltration of surface runoff into the well casing and the well annulus; to prevent accidental damage or vandalism of the well; and to minimize physical hazards.

The surface completion of a monitoring well involves installing the following components (Figure 1):

- Surface seal;
- A protective casing (for an above-ground surface completion) or a traffic-rated well vault (for a flush-to-ground completion);
- Ventilation hole (where explosive gases are known or suspected);
- Drain (or "weep") hole in protective casing (for an above-ground surface completion);
- Well cap;
- Lock;

- Well tag; and
- Guard posts (for an above-ground surface completion).

A permanent metal tag attached to the well should be inscribed with: well identification, top-of-casing elevation (in mean sea level [msl]), total as-built depth, and screened interval.

3.12.1 Above-Ground Completions

In above-ground well completions, the surface seal should form a well apron extending two feet in all directions from the protective casing (Figure 1). The well apron (at least 4 inches thick) should slope away from the casing to drain surface water radially away from the protective casing and to prevent leakage down the outer wall of the protective casing. To minimize frost damage in cold climates, the well apron should not extend beyond the borehole (Nielsen 2006).

Because painted numbers wear away, the well identification (name and number) should be inscribed in the concrete apron. A metal well tag inside the protective casing should also be inscribed with the well identification (name and number) and other critical information (Section 3.12).

A protective casing (also known as a standpipe, stickup pipe, or riser) should be installed around the well casing to prevent damage or unauthorized entry. The protective casing should be anchored below the frost line (where applicable) into the surface seal and extend at least 18 inches above the ground surface. A 0.25-inch diameter vent hole in the standpipe is recommended to allow the escape of any potentially explosive gases that may accumulate within the well. A drain hole in the protective casing (at about 6 inches above the ground surface) prevents water from accumulating and, in cold climates, freezing around the well casing. Although water should not be able to accumulate within the protective casing in a properly designed and located well, a drain hole is recommended as a precautionary measure. The space between the protective casing and the well casing may be filled with pea gravel to allow the retrieval of tools and to prevent small animal/insect entrance through the drain hole. A cap should be placed on the standpipe to prevent tampering or the entry of any foreign materials.

A lock should be installed on the cap of the standpipe and/or the well cap to provide security. To prevent corrosion or jamming of the lock, a protective cover should be used. Care should be taken when using lubricants such as graphite or petroleum-based sprays to lubricate the lock, as lubricants may contaminate groundwater samples. Locks should not be lubricated on the day the well is sampled, and gloves that are worn while lubricating the lock should be changed prior to initiating other activities at the well.

Where explosive gases are known or suspected, the well cap should be vented to allow escape of potentially explosive gases and equilibration with barometric pressure.

To guard against accidental damage to the well from traffic, concrete or steel bumper guard posts or bollards should be installed around the edge of the concrete apron. The guard posts (generally 3-feet high) should be located within 3 or 4 feet of the well and should be painted orange and/or fitted with reflectors to reduce the possibility of vehicular damage. The area surrounding the well should be kept clear of brush, debris, and waste materials.

3.12.2 Flush-to-Ground (and Below-Ground) Completions

Flush-to-ground completions are used in areas such as roadways, parking lots, operating facilities, and gas stations. In flush-to-ground completions, a traffic-rated well vault is installed around the well casing. Other measures taken to prevent the accumulation of surface water in the vault/box include: completing the structure with a surrounding grade or apron (such that the completion is slightly above original ground surface); outfitting the protective structure with a steel lid or manhole cover and rubber gasket; ensuring a watertight bond between the surface seal and protective structure; and, using watertight locking well caps.

Where explosive gases are known or suspected, the well cap should be vented to allow escape of potentially explosive gases and equilibration with barometric pressure.

The vault lid should be clearly and permanently marked “MONITORING WELL” (DWR 1991). A metal well tag inside the vault should be inscribed with the well identification (name and number) and other critical information (Section 3.12).

Surface completion is described in detail by Aller et al. (1986) and Nielsen (2006).

3.13 Accessibility

All outdoor wells should be located an adequate distance from buildings and other structures to allow access for well maintenance, repair, modification, and decommissioning.

Similarly, all indoor wells should be located a safe distance from load-bearing walls/supports, footings, and utilities to allow access for well activities.

3.14 Well Surveying

The collection of information related to the locations of groundwater monitoring wells constitutes land surveying (as the term is defined in California Business and Profession Code §8720 et seq.) and requires a license, unless a statutory exemption applies.

Surveying and reporting of electronic geographic information on the well locations should be consistent with the requirements of the State Water Resources Control Board's (SWRCB's) GeoTracker system (established pursuant to Cal. Code Regs., tit. 23, §3893, and Cal. Code Regs., tit. 27, div. 3, subdiv. 2, chap. 2). Detailed information can be found on SWRCB's GeoTracker website. The survey should note the coordinates of any temporary benchmarks. In addition, all monitoring wells should be accurately located with respect to permanent or semi-permanent site features.

For electronic submittal of information (ESI), SWRCB's GeoTracker requires the use of the North America Vertical Datum of 1988 (NAVD88) for vertical (z) coordinates and NAD83 for horizontal (x, y) coordinates. GeoTracker requires that the relative elevations of locations on the site be measured within 0.01 foot. The accuracy of the absolute elevation (tied to the vertical datum) may be greater than 0.1 feet. The X and Y coordinates are to be measured in decimal degrees and reported to 7 decimal points.

Because the well casing is less susceptible to disturbance (e.g., frost heave, collision) than the protective casing or well apron, the surveyed reference mark should be permanently marked or notched on the top of the well casing (preferably on the north side) and should be resurveyed regularly (e.g., every 5 years). Well locations should be resurveyed if damage to the well casing (with surveyor's notch) is noted or if anomalous groundwater elevation data are measured. Re-surveying may also be warranted if damage to the protective casing or surface completion is observed, as such damages may suggest shifting or settling of the well. Areas susceptible to subsidence (e.g., landfills, or heavily-pumped areas) may require more frequent surveying. Replacement of the well vault and/or apron due to corrosion or other damage will necessitate re-surveying.

3.15 Well Alignment and Plumbness

During construction, well alignment may need to be assessed to check for proper screen placement and smooth passage of sampling and pumping equipment. Well alignment can be checked by passing a 20- to 40-foot length of steel pipe through the well casing. The diameter of the steel pipe should be no less than 0.5 inches smaller than the diameter of the well. The pipe should descend to the bottom of the well without binding. For shallow wells (e.g., 40 feet or less), an alternative procedure may be chosen. Another alternative is to quantitatively measure alignment through a deviation test.

Well deviation tests should be performed for any well greater than 200 feet deep. DQOs for alignment and plumbness should be included in the work plan. The American Water Works Association (1984) discusses procedures for assessing alignment and plumbness of wells.

In horizontal wells, directional drilling of the pilot test hole (e.g., using hand-held radio-detection equipment), along with video-logging, ensures horizontal alignment of well components. Plumbness of the vertical components of a horizontal well can be addressed as discussed in the first paragraph of this section.

3.16 Well Development

After construction, groundwater monitoring wells should be developed to:

- Correct damage to the geological formation caused by drilling (e.g., by removing drilling mud from the formation and mudcake from the borehole wall);
- Restore the natural water quality of the aquifer near the well;
- Optimize hydraulic communication between the geologic formation and the well screen (e.g., improve the yield of the well); and,
- Create an effective filter pack around the well screen.

Well development is necessary to provide groundwater samples that represent natural undisturbed hydrogeological conditions. In particular, a properly installed and developed well produces samples of acceptably low turbidity (i.e., less than 5 NTUs, as recommended by USEPA [1986]). Turbidity is caused by fine-grained materials entering the well. Fine-grained materials include: silts, clays, colloids, and organic material (e.g., peat). Low turbidity is desirable because turbidity may interfere with subsequent analyses, resulting in biased data, especially for COCs that sorb to fine-grained materials (e.g., metals). As development proceeds, well water becomes more clear (i.e., less turbid).

Development stresses the formation and the filter pack with a back and forth motion around the screen, so that the fine-grained materials are mobilized, pulled through the well screen into the well, and removed from the well by pumping.

Wells with natural filter packs (i.e., direct-contact, exposed screen, or no-pack wells) require rigorous development, especially if the well screen is exposed during driving, to remove sediments from screen slots and the adjacent formation.

At the start of development, the water in the well contains a wide range of grain sizes from the geologic formation and the well water is turbid. As development proceeds and water is withdrawn from the well, at first, large grains are retained by the filter pack, resulting in a layer of coarser grains against the well screen. Then, layers of progressively smaller grains are retained. This sorting process creates a graded filter pack which is essential for reducing turbidity (Izrael et al. 1992).

Development also removes any foreign materials (e.g., drilling water, muds, and chemical additives) that may have been introduced into the well borehole during drilling and well installation.

Inducing movement of groundwater into the well in only one direction causes bridging of particles (with voids under the bridges): the back and forth motion of well development breaks down bridges, resulting in a stable filter pack.

Common methods for developing wells discussed by Aller et al. (1989) and Driscoll (1986) include:

- Pumping and overpumping,
- Backwashing (alternately starting and stopping a pump),
- Surging with a surge block,
- Bailing,
- Jetting with water,
- Airlift pumping, and
- Air surging.

The well development methods that are generally acceptable are: bailing, surging with a surge block, pumping (and over-pumping), backwashing (by turning the pump on and off), or combinations of these methods.

Overall, the most effective and efficient method available for inducing flow reversal during well development is surging using a surge block, with pumping or bailing of fine-grained materials.

A typical surge block is a length of pipe (usually PVC) with one or more large steel washers (or rubber disks between wooden disks) fitted to the end of the PVC pipe (Sterrett 2007). The washers should just fit inside the well casing. Manufactured surge blocks are also available. The surge block is inserted into the well and acts like a plunger as it is repeatedly lifted and lowered (1-foot to 2-feet) through the saturated screened interval. Once the entire screened interval is surged, the process should be repeated until the well water is clear. For effective well development, the surge block may need to be carefully lifted and lowered for several hours, with periodic pumping or bailing of the fines.

If a centrifugal pump or manual surging is used, surging progresses from the bottom to the top of the screened interval (or open borehole).

If the OD of a submersible pump is close to the ID of the well casing (within 1/4 to 1/8 inch), a submersible pump can be used as a surge block. In such a case, surging should progress from the top to the bottom of the well screened interval, to prevent sand locking of the pump. Fine-grained sediments and high COC concentrations (e.g., LNAPLs) may also clog or damage submersible pumps (Nielsen 2006).

The following is a general procedure for developing a well by surging and pumping of fines (Israel et al. 1992):

1) Record the static water level and total well depth.

2) Set the pump in the middle of the well screen or in the middle of the standing water column and record the pumping rate. Work the pump up and down across the screened interval while pumping. Pump at a high rate (e.g., 10 to 15 gallons per minute) until at least ten well volumes have been removed or until turbidity

reaches the desired level as measured using a turbidity meter. Ten well volumes is a rule-of-thumb often used by GSB (and is required by the State of Wisconsin [NR 141.21(1)(b)]). Record the pumping rate and volume of water removed.

3) Discontinue pumping and begin surging using a properly designed surge block and proper surging technique. Use a gently approach at first to observe how the well performs. More aggressive methods can be used as well development proceeds.

4) Measure and record well depth (to assess whether fine materials are accumulating in the bottom of the casing). Measure and record turbidity. Repeat Step 2. If the well has been properly designed, the amount of pumping required to achieve the desired turbidity during the second and subsequent pumping cycles will be substantially less than the amount of pumping required during the first pumping cycle.

5) Repeat surging and pumping until the well yields water of acceptable turbidity at the beginning of a pumping cycle. A good way to ensure that development is complete is to shut the pump off during the last anticipated pumping cycle, leave the pump in place, and re-start pumping at a later time. The turbidity of the discharge water should remain low when pumping is re-started. Record the total volume of water removed.

Surging can potentially damage the well screen or the filter pack or knock out the bottom plug. For example, PVC well screens of low strength may be damaged during vigorous development. Another example: in low permeability zones, excessive fines may penetrate the filter pack, thwarting the creation of a graded filter pack, and well yields may be very low. Development options are also limited for well casings with narrow diameters (e.g., DP wells). Wells developed in bedrock may require special development protocols (Israel et al. 1992): for example, surging may damage open borehole walls. Therefore, depending on the hydraulic conductivity of the screened zone, the diameter of the well, the well yield, and other factors, pumping (without surging) may suffice for some wells.

If a well has been damaged during installation or development (e.g., the bottom plug has blown out), a work plan for corrective action (e.g., installing a dummy plug or otherwise sealing the bottom of the well casing), well decommissioning, and/or replacement should be submitted.

Effective and efficient well development is possible only with an adequate flow rate during water withdrawal. Fine-grained materials that have been drawn into the well should be removed to the greatest degree possible. Therefore, one of the following pumping methods, listed in the order of preference, should be used in conjunction with a properly-sized surge block:

- Centrifugal pump capable of removing fines (if the water level is within suction-lift distance);

- Electric submersible pump capable of pumping fines; or,
- Properly designed and operated air-lift system (with prior regulatory approval).

Pumping rates during development should be recorded: pumping rates during subsequent purging and sampling rates should not exceed the maximum pumping rate used during development.

Well development methods and equipment that alter the chemical composition of the groundwater should not be used. Development methods that involve adding water (including water pumped from the well) or other fluids to the well or borehole, or that use air to accomplish well development, are generally discouraged. Consequently, methods that are unsuitable in most cases for monitoring well development include: jetting, airlift pumping, and air surging.

Prior approval should be obtained from the lead regulatory agency prior to introducing air, water, or other fluids into any well for the purpose of well development. Any water introduced into the well during well development should be from a known and acceptable source. If the water quality is unknown or suspect, the water should be analyzed (e.g., for water quality parameters and COCs) prior to use. If water is added, two to three times the volume of added water should be removed during development (Israel 1992).

Airlift pumping may be acceptable if it is demonstrated that appropriate measures will be taken for preventing air contact with the formation, and for preventing the entry of compressor oils into the well.

It is usually unacceptable to use chemicals for developing monitoring wells. However, if chemicals are approved for well development, extreme care should be exercised. Chemicals introduced for development must be completely removed from the well, filter pack, and water-bearing zones accessed by the well immediately after development operations are completed (DWR 1991).

If well drilling, installation, or completion has altered groundwater quality chemically in the vicinity of the well, well development should aid in restoring groundwater quality within the well to ambient groundwater quality. The ability of a well development method to remove clays from the sides of the borehole should be considered, because clays retained in the borehole may alter the chemical composition of groundwater in the well. In addition to turbidity, periodic monitoring of groundwater during well development, for water quality parameters such as specific conductance, temperature, and pH, should be performed. The reproducibility of these field parameters indicates that groundwater chemistry in the well has been restored to ambient quality.

Monitoring wells should not be developed before well sealant materials have set or cured, generally a minimum of two days after emplacement. Some counties require longer times between well construction and development. For example, some San Francisco Bay Area counties require a minimum of 72 hours for sealants to set.

Information obtained from any aquifer tests conducted on the well should be used to establish the initial yield of the well, and these data can be used for periodic redevelopment and maintenance assessments.

Waste water from well development should not be released to the ground surface. Waste water should be captured and containerized. The work plan for well installation should describe how the waste water from well development will be characterized, handled, stored, and disposed. Disposal of waste water to a publicly owned treatment works (POTW) may be permitted.

The report of well installation (Section 3.17) should summarize well development, including: dates and times that seals were installed, dates and times of development, development procedures, tools (surge block, pump, and other equipment), rate of purging, volume of water removed, turbidity measurements, measurements of field parameters, deviations from the work plan, problems encountered, and corrective actions taken.

3.16.1 Turbidity

Groundwater should be collected periodically and measured for turbidity during well development and at the completion of well development. The final turbidity measurement should be recorded on the well construction log. A well that cannot produce low turbidity water (i.e., less than 5 NTUs) may have been improperly designed (e.g., mismatched filter pack and formation materials or mismatched filter pack and screen slot size). Improper or incomplete development may also result in high turbidity. If a well is not producing low turbidity groundwater, then the development documentation should demonstrate that proper well completion and development measures have been employed.

In some hydrogeological environments, high turbidity may persist despite appropriate design and development. For example, groundwater in wells in fractured rock or karst aquifers may become muddy after periods of rainfall, even though the water is free of turbidity during fair weather. Wells completed in peat, clay, or silt may also produce consistently turbid samples. Water within such formations may not be turbid: that is, fine-grained particles may not migrate in groundwater within the formation. However, fine-grained materials may migrate into the coarser-grained filter pack and into the well, resulting in turbid samples. Wells in such hydrogeological environments will normally be considered to have been properly installed and developed, despite turbidity greater than 5 NTUs. However, if it is common knowledge that a hydrogeological environment produces turbid samples, evaluation of alternate well designs might be warranted (e.g., pre-packed screens).

If turbidity of less than 5 NTUs is not achievable due to high clay/silt content (or other site-specific conditions), then alternate DQOs for turbidity (e.g., during development and during purging prior to sampling) should be discussed with regulatory agencies. In some cases, based on previous site experience, removal of a specific volume of water (e.g., three-casing volumes during purging) may be acceptable.

Achieving low turbidity is critical for metals but may be less important for VOCs and semi-VOCs (unless the VOCs and semi-VOCs are sorbed to fine-grained materials or colloids). Alternate sampling protocols may be adopted to resolve turbidity issues (e.g., no-purge sampling or low flow purging and sampling) (CalEPA 2008). Filtering may be required for some analyses (e.g., Title 22 Metals).
Turbidity that increases in a well over time may indicate that the well is silting up, that the initial development was not adequate, that the pump rate during purging or sampling is too high, or other factors. Redevelopment may help to resolve these issues.

The determination of whether to address turbidity during sampling (e.g., using no-purge sampling) and analysis (e.g., by filtering in the field or laboratory), or to redevelop, decommission, or replace a well, should be made by the project manager in consultation with an agency geologist.

3.17 Documentation of Well Design, Construction, and Development

Information on the design, construction, and development of each well should be compiled and provided to DTSC in a report. Well design and construction documentation is also needed for evaluating decommissioning options.

Such information should include: 1) a boring log that documents well drilling and associated sampling (see CalEPA 2013); 2) a well construction log; and, 3) an as-built well construction diagram. The following information should be presented on the boring log, the well construction log, or the well construction diagram—or, within the text of the report—as appropriate.

- Name of driller and drilling company;
- Drill rig make and model;
- Well name/number;
- Associated borehole identification (name/number), if different from the well;
- Date/time of well construction;
- Latitude and longitude;
- Well location description;
- Sketch showing site features;
- Borehole diameter and well casing diameter;
- Depth to first-encountered water;
- Depth to water upon completion;
- Well depth (±0.1 feet);
- Casing (materials, length, casing and screen joint type);
- Screened interval(s) (materials, slot size/design);
- Centralizers (material, locations);

- Primary filter pack (material, gradation, uniformity coefficient and size, volume [calculated and actual], and placement method);
- Fine sand transition zone or secondary filter pack or (composition, volume, and placement method);
- Bentonite seal above the fine sand transition zone (composition, volume, thickness, and placement method);
- Annular sealant (composition; volume [calculated and actual], and placement method);
- Surface sealant (composition/cement type; volume [calculated and actual], and placement method);
- Surface seal and well apron design/construction;
- Type and design/construction of protective casing;
- Well cap and lock;
- Ground surface elevation (±0.01 feet); and,
- Survey reference point elevation (±0.01 feet) (i.e., elevation of notch on top of the well casing).

Documentation supporting the well design should be included in the report:

- Selection of:
  - construction materials for casing and screen;
  - well diameter, screen length, and screen slot size;
- Selection and installation of filter pack and annular sealants;
- Security of the well; and,
- Survey methods for well location and elevations of the top of the casing.

A summary of well development should also be included (as described in Section 3.16).

Documentation of as-built well construction is required to be reported to DWR (by the licensed well drilling contractor) or to the local well-permitting agency, using forms provided by DWR (Cal. Water Code §13751 (a) and (b)). DWR's 40-page pamphlet, *How to Fill Out a Well Completion Report, Instruction Pamphlet* (DWR 2007), contains detailed instructions. It is recommended that DWR's well completion forms (with attachments) be included in the report submitted to DTSC, provided that the well owner has signed a release from confidentiality.

3.18 Specialized Well Designs

Special groundwater monitoring well designs should be used when:

- Dedicated pumps are used to withdraw groundwater samples; or,
- Separate-phase LNAPLs or DNAPLs may be present.

Dedicated groundwater sampling devices are generally constructed of fluorocarbon resin or stainless steel. The design of the dedicated sampling system should allow access to the well for: conducting aquifer tests; maintaining the well (e.g., redevelopment); and, making water level measurements. Dedicated sampling systems should be periodically inspected to ensure that the equipment is functioning reliably. Samples should be withdrawn from the dedicated sampling system to evaluate the operation of the equipment, and the equipment should be checked for damage.

Where LNAPLs and DNAPLs are presumed present, the well should be designed to allow collection of discrete samples of light and/or dense phases. In certain cases, well screens that extend from above the water table to the lower confining layer may be appropriate, but more frequently the presence of immiscible phases will require that well clusters or multilevel sampling devices be installed.

Where well clusters are employed, one well in the cluster may be screened at horizons where LNAPLs are expected and another may be screened at horizons where DNAPLs are expected. Other wells may be screened within other portions of the aquifer to monitor dissolved-phase VOCs.

As noted in *1.4 Limitations*, the design of specialized remediation wells (e.g., for extraction, injection, thermal applications) is outside the scope of this guidance. Readers are encouraged to consult engineering and geological experts regarding the design of such wells. However, the general design principles for monitoring wells, as described in this document, also apply to remediation wells. For example, in extraction wells, the well screen must be strong enough to accommodate pumping stresses and the diameter of the well casing must be sized to accommodate the pump.

3.19 Evaluation of Existing Wells

Existing monitoring wells should meet the construction and performance standards presented in the DWR (1991) and county, city, or district ordinances. There are two situations in particular where wells may fail to meet the performance standards: 1) where existing wells are physically damaged, and 2) where there is little or no documentation of how existing wells were designed and installed.

Wells that are physically damaged, or wells for which there is not sufficient documentation of design and construction, may need to be repaired or replaced. In addition, replacement may be warranted if: wells produce consistently turbid samples ($\geq$5 NTUs); wells were not properly designed or constructed; or, wells do not meet performance standards outlined in this document. The design, installation, development, and decommissioning of replacement monitoring wells and piezometers (and associated measurement, sampling, and analytical devices) should be documented and reported. Names of replacement monitoring wells should be distinguished from the names of original monitoring wells. For example, the addition of an “R” to the original name can indicate that the well is a replacement well.

Routine inspections should be conducted during sampling and results of inspections recorded. Recommendations should be made for corrective action, along with a schedule for corrections. Documentation of corrective action should be included in a report.

Maintenance items to be considered in an inspection include:

- Well name is present and legible;
- Well tags are present and are legible;
- Well is visible and accessible;
- Surrounding area is free of vegetation, waste, and debris;
- Well is not flooded or frost-damaged;
- Locks are present and in good condition (i.e., no rust);
- Well cap is present and is watertight;
- Protective casing is not damaged or corroded;
- Surface pad exists and is not cracked or deteriorated;
- Top-of-casing survey marks exist and are legible;
- Total depth of well as-measured is compared to total depth of well as-built;
- Silting-up of well is noted if present;
- Guard posts (if present) are in good condition; and,
- Well vault (if present) is in good condition (i.e., no standing water, bolts are tight, and seals are secure).

Well tags inscribed with: well name/number, top-of-casing elevation (in msl), total as-built depth, and survey date are recommended.

Geophysical downhole evaluations and hydraulic conductivity tests may be needed—to determine whether sediment removal or redevelopment is needed.

Wells may need to be re-developed if silted-up (e.g., siltation exceeding 5% of the screened interval). Wells may need to be re-conditioned if biofouling has reduced the hydraulic conductivity of the filter pack or well screen—or, if the water chemistry of the well is not representative of the nearby water-bearing zone. Prior approval of the regulatory agency is required for chemical cleansing and re-conditioning of wells. RWQCB and local ordinances may also address chemical cleaning of monitoring wells.

Video-logging may be useful in cases where there is little or no documentation of how the well was designed and constructed, or if the current well condition is unknown.

3.20 Decommissioning Groundwater Monitoring Wells and Boreholes

A well is considered abandoned or permanently inactive if it has not been used for one year, unless the owner demonstrates an intention to use the well again (DWR 1991).

Groundwater contamination resulting from improperly decommissioned wells and boreholes is a serious concern. Abandoned, inactive, and improperly constructed wells and boreholes should be properly decommissioned to:

- Eliminate physical hazards;
- Prevent surface water contamination of groundwater;
- Conserve aquifer yield and hydrostatic head (e.g., prevent artesian flow from an abandoned well); and,
- Prevent mixing of subsurface water (i.e., cross-contamination between zones or within a zone).

An open, unused borehole or an improperly constructed or unused well should be decommissioned in accordance with DWR (1991) and local requirements. ASTM (2012a) provides updated decommissioning standards.

<u>Borehole decommissioning</u>

- Completely fill the entire borehole with grout from the bottom of the borehole to within a few (5 or less) feet of the ground surface, and
- Backfill the uppermost few feet with grout or clean fill material. Clean fill material is sometimes acceptable, and preferred over grout, to facilitate utility installation or site development (e.g., when grading is anticipated).

<u>Preliminary work</u>

Each well should be investigated prior to destruction to determine or confirm details of its condition and construction. The as-built well construction log and field documentation should be reviewed. Obstructions to filling and sealing the well should be removed. Debris, oil, and other contaminants that may interfere with well destruction (e.g., chemicals incompatible with grout) should also be removed. Downhole cameras and geophysical techniques may be used to determine well construction and assess obstructions, cracks, or voids in the well casing.

<u>Wells constructed according to DWR standards</u>

If the monitoring well is located in an area of known or potential pollution or contamination, the monitoring well casing, and any other significant voids within the well (e.g., in the annulus or adjacent formation), should be completely filled with sealing material. Perforating or puncturing the well casing may be necessary to ensure that the well casing and voids are completely filled. Sealing material may have to be installed under pressure to ensure that the monitoring well is properly filled and sealed.

<u>Wells *not* constructed according to DWR standards</u>

If well construction and maintenance were not sufficient to ensure that filling the well and voids with grout would prevent potential water quality degradation and/or migration of contaminants, monitoring well abandonment should entail:

- Pulling or over-drilling the entire well casing, including telescoped casings and multi-well completions, then completely filling the hole, with grout under pressure, to within five feet (or less) of the surface; or

- In a stepwise fashion (from the bottom up), ripping or perforating the well screens, and all casing intervals adjacent to fine-grained or low-permeability strata (as identified from borehole logs), and filling with grout under pressure to within five feet (or less) of the surface; then,

- Removing the uppermost five feet (or less) of casing, annular seal, and surface completion—and backfilling with clean fill material.

Casing, filter pack, and annular sealant may be left-in-place during sealing operations, if the enforcing agency agrees they cannot or should not be removed. In such a case, appropriate sealing material should be placed in the well casing, filter pack, and all other significant voids within the entire well boring. This procedure is referred to as sealed-in-place. Perforation/puncturing and sealing under pressure may be required.

Ripping/perforating the well casing may not be required for wells screened at the water table only, if the well screen does not cross several zones.

Within water-bearing zones, cement-bentonite mixtures are commonly used. Within the unsaturated zone, cement without bentonite should be used, to avoid desiccation of the bentonite and consequent shrinkage of the seal, especially in arid areas (DWR 1991). Compositions of sealant materials (i.e., neat cement, sand cement, concrete, and bentonite) are described in DWR (1991). Depending on site conditions, other sealing materials may be appropriate (e.g., high-solids bentonite, sand/bentonite mixtures, or cement with aggregate). ASTM (1992) contains detailed information on grout mixtures. Local agencies may have specific requirements which should be incorporated into a decommissioning work plan.

To prevent bridging and ensure a good seal, grout should be kept under pressure during placement. This can be achieved by using a tremie pipe to feed grout into the borehole. At all times, the opening of the tremie pipe should be submerged several (2 or more) feet below the level of grout in the borehole. The amount of submergence depends on the amount of pressure needed for adequate penetration of grout into the formation. Free-fall placement of grout is not an acceptable practice. In some cases, perforation tools may be used by the driller to pierce the casing and allow pressurized grout to seal the entire borehole.

Decommissioning approaches should be considered early on (i.e., during well design), to ensure that borehole sealant materials (e.g., cement) will be not alter groundwater chemistry or be incompatible with contaminants.

Destruction or alteration of wells must be reported to DWR on forms supplied by DWR. Copies of well destruction forms should also be provided to DTSC.

County, city, and local districts may have ordinances for well decommissioning. Inspection by local authorities may also be required.

Well abandonment by the use of specially-designed explosive charges may be successful in certain circumstances. Explosives may ensure that grout is pushed out into the formation. Explosives should be used with special care to prevent damage to surrounding structures and to any natural barriers to the movement of poor-quality water, pollutants, and contaminants. Explosives may only be used by a properly-trained person: in addition to the C-57 Water Well Contractor’s License, a current California Blaster’s License is required (Cal. Code Regs, tit. 8, §344.20). Prior regulatory approval is critical, especially since public notices may need to be developed when explosives are used on a regulated site.

Well decommissioning details should be recorded and reported to DTSC, including:

- Location of well;
- Method of decommissioning;
- Total well depth;
- Well diameter (hole diameter if over-drilling);
- Depth to water;
- Grout composition;
- Calculated volume of the well or borehole and volume of grout used;
- Depth to casing separation and length removed;
- Well decommissioning permit number and date; and,
- Other information listed in Section 3.17 (e.g., date, name of driller, and drill rig).

Local agencies often have a keen interest in well decommissioning and may require advance notice and the presence of an inspector. Local ordinances may specify record-keeping (e.g., of surface completion details) that is more stringent than discussed in this document or its references. Regulatory agencies, as well as experienced geologists, geotechnical engineers, and drillers, should be consulted prior to decommissioning a well or borehole to ensure that decommissioning is appropriately performed and to ensure compliance with state and local laws.

Well water displaced during well decommissioning should not be released to the ground surface. Displaced water should be containerized. The work plan for well decommissioning should describe how waste water will be characterized, handled, stored, and disposed. Disposal to a POTW may be permitted.

Aller et al. (1989), ASTM (1992), and CalEPA (2013) provide additional information on well decommissioning.

3.21 Investigation-Derived Waste (IDW)

IDW, including drill cuttings and wastewater from monitoring wells and exploration holes in areas of known or suspected contamination or pollution, should be disposed of in accordance with all applicable federal, state, and local requirements. Used drilling mud and/or cuttings from drilling operations should not be used as sealant material for wells or boreholes (DWR 1991). The owner/operator (i.e., the responsible party) is required to properly dispose of all waste materials (e.g., drill cuttings and wastewater). Work plans should describe how waste materials will be characterized, handled, stored, and disposed, and identify licensed haulers and permitted treatment, storage, and disposal (TSD) facilities. Field reports should document IDW characterization, handling, storage, and disposal: for example, chemical analytical laboratory reports, shipping documentation, bills of lading and/or manifests should be included.

3.22 Workplace Safety

Workplace safety should be emphasized during all phases of well installation and decommissioning. Appropriate measures to protect the health and safety of individuals should be described in a site-specific Health and Safety Plan (HASP), including a job-specific hazards analysis. HASPs are considered as integral parts of work plans for well installation or decommissioning. HASPs should be submitted as appendices to work plans and should be consistent with *Site Specific Health and Safety Plan Guidance Document for Sites under DTSC Purview* (CalEPA 2011).

Safety measures usually include: utility clearance, maintaining a safe distance from power lines, stopping of work during lightning storms and during high wind conditions, minimizing exposure to potentially explosive or toxic gases, and using proper personal protection equipment (e.g., hardhats, vests, and hearing protection). Pressure grouting involves specific hazards (e.g., exploding well caps). Therefore, drillers should be stationed at a safe distance from pressure grouting equipment.

Training requirements should be identified and training participation should be verified. Minimum training requirements include the 40-hour Hazardous Waste Operations and Emergency Response Standard (HAZWOPER) training, and 8-hour annual HAZWOPER refreshers.

4.0 WELL CASING AND SCREEN MATERIALS

4.1 General Considerations

Historically, well casings and screens were produced predominantly for water supply wells and the selection of well casing and screen material focused on: structural strength; durability in long-term exposure to natural groundwater environments; open screen areas; and, ease of handling.

Currently, well casing and screen materials used for groundwater monitoring at contaminated sites are typically PVC Schedule 40 for shallow wells and PVC Schedule 80 (which is stronger than Schedule 40) for deeper wells. Stainless steel wells and screens are used at some sites. Despite this rather uniform approach, the design process related to materials selection should not be overlooked. That is, the selection of well casing and screen materials should be site-specific, consistent with the CSM and with the DQOs established for individual wells at the site. Therefore, a summary of general principles related to material selection and basic research on the topic has been retained in this revised guidance.

The well casing and screen: provide access from the ground surface to some point in the subsurface; prevent borehole collapse; permit hydraulic measurements and groundwater sampling; and (for casing), prevents hydraulic communication between separate water-bearing zones within the subsurface.

Monitoring well casing and screen materials should:

- Maintain their structural integrity and durability in the environment in which they are used over their operating life;
- Be resistant to chemical and microbiological corrosion and degradation in contaminated and uncontaminated waters;
- Be able to withstand the physical forces acting upon them during and following their installation, and during their use--including forces due to suspension in the borehole, grouting, development, purging, pumping, sampling, and forces exerted on them by the surrounding geologic materials (e.g., lithostatic, hydrostatic, and seismic); and,
- Not chemically alter groundwater samples, especially with respect to COCs and water quality standards.

Laboratory studies of the effects of well casing materials on either inorganic or organic dissolved constituents in groundwater have demonstrated the potential for well casing-related alteration of groundwater samples. However, the studies are inconclusive or incomplete and should be viewed as tentative.

The following discussion of casing and screen materials comes primarily from *Handbook of Suggested Practices for the Design and Installation of Ground-Water*

Monitoring Wells (Aller et al. 1989), with additional information from various references, as cited. The fundamental research previously conducted (and cited in this document) is still current. However, readers are encouraged to check recent research findings (e.g., in professional journals), especially when new materials are proposed or selected or when emerging contaminants (e.g., perfluorinated compounds [PFCs]) are encountered.

This guidance, along with the technical criteria provided below, aid in the selection of appropriate well materials. In addition to references cited by Aller et al. (1989), the following references may also be useful:

- Cowgill, U.M. 1988. *The Chemical Composition of Leachate from a Two-Week Dwell-Time Study of PVC Well Casing and Three-Week Dwell-Time Study of Fiberglass Reinforced Epoxy Well Casing*, in A.G. Collins and A.I. Johnson, eds., *Ground-Water Contamination: Field Methods*, *ASTM STP 963*, ASTM, Philadelphia, PA, pp. 172-184.

- Gillham, R.W. and S.F. O'Hannesin. 1990. *Sorption of Aromatic Hydrocarbons by Materials Used in Construction of Ground-Water Sampling Wells*, in D.M. Nielsen and A.I. Johnson, eds., *Ground-Water and Vadose Zone Monitoring, ASTM STP 1053*, ASTM, Philadelphia, PA, pp. 108-122.

- Jones, J.N. and G.D. Miller. 1988. *Adsorption of Selected Organic Contaminants onto Possible Well Casing Materials*, in A.G. Collins and A.I. Johnson, eds., *Ground-Water Contamination: Field Methods, ASTM STP 963*, ASTM, Philadelphia, PA, pp. 185-198.

- Parker, L.V., T.F. Jenkins, and P.B. Black. 1989. *Evaluation of Four Well Casing Materials for Monitoring Selected Trace Level Organics in Ground Water*, *CRREL Report 89-18*. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH 03775.

4.2 General Casing and Screen Material Characteristics

The selection of appropriate materials for monitoring well casings and screens should consider several site-specific factors, including:

- Geologic environment (e.g., well depth and geochemistry of soil and groundwater);
- Types and concentrations of suspected contaminants;
- Design life of the monitoring well; and,
- Potential for the well to be converted for injection or extraction.

The selection of appropriate materials for well screens and casing requires some knowledge of the site, including: site history (e.g., chemicals used, stored, and disposed); regional information (e.g., stratigraphy and groundwater quality); and, data from preliminary investigations. Selection criteria are summarized in *Table 1 General recommendations for selection of well casing and screen materials*.

Selection of well construction materials can be based on scientific studies or on field data collected from sites with similar hydrogeologic settings and similar COCs.

The selection of casing and screen materials may vary within a well network, depending on the purposes of individual wells and on localized site conditions (e.g., COCs and high versus low concentrations). Screen and casing materials may even vary within a well. In some cases, site-specific comparative performance studies may be needed.

Two characteristics that directly influence the performance of casing and screen materials in groundwater monitoring applications are:

- Strength,
- Chemical resistance, and
- Chemical interference.

These characteristics are discussed in more detail below.

4.2.1 Strength-Related Characteristics

Well casing and screen materials should maintain their structural integrity and durability in the environment over their operating life. Monitoring well casings and screens should be able to withstand the physical forces acting upon them during and following their installation, and during their use, including forces due to suspension in the borehole, grouting, development, purging, pumping, sampling, and forces exerted on them by the surrounding geologic materials.

When casing strength is evaluated, three separate yet related parameters should be evaluated:

- Tensile strength,
- Compressive strength, and
- Collapse strength.

Comparative strengths of well casing materials are presented in *Table 2 Comparative strengths of well casing materials*.

4.2.1.1 Tensile Strength

The tensile strength of a material is defined as the greatest longitudinal stress the material can bear without pulling the material apart. Tensile strength of the installed casing varies with composition, manufacturing technique, joint type, and casing dimensions. For monitoring wells, the selected casing and screen materials should have a tensile strength capable of supporting the weight of the casing string when suspended from the surface in an air-filled borehole. The tensile strength of the casing joints is equally as important as the tensile strength of the casing. Because the joint is generally the weakest point in a casing string, the joint strength will determine the maximum axial load that can be placed on the casing. By dividing the tensile strength by the linear weight of casing, the maximum theoretical depth to which a dry string of casing can be suspended in a borehole can be estimated. When the casing is in a borehole partially filled with water, the buoyant force of the water increases the length of casing that can be suspended. The additional length of casing that can be suspended depends on the specific gravity of the casing material.

4.2.1.2 Compressive Strength

The compressive strength of a material is defined as the greatest compressive stress that a substance can bear without deformation. Unsupported casing has a much lower compressive strength than installed casing that has been properly grouted and/or backfilled, because vertical forces are greatly diminished by soil friction. Casing failure due to compressive strength limitation is generally not an important factor in a properly installed monitoring well.

4.2.1.3 Collapse Strength

As important as tensile strength is the final strength-related property considered in casing and screen selection, which is collapse strength. Collapse strength is defined as the capability of a casing to resist collapse by any and all external loads to which it is subjected both during and after installation.

The resistance of casing to collapse is determined primarily by the OD and the wall thickness. Casing collapse strength is proportional to the cube of the wall thickness. Therefore, a small increase in wall thickness provides a substantial increase in collapse strength. Collapse strength is also influenced by other physical properties of the casing material including stiffness and yield strength.

Casings and screens are most susceptible to collapse during installation before placement of the filter pack or annular seal materials around the casing. Although the casing may collapse during development, once a casing is properly installed, collapse is seldom a concern (National Water Well Association and Plastic Pipe Institute, 1981). External loads on casing that may contribute to collapse include:

- Net external hydrostatic pressure produced when the static water level outside of the casing is higher than the water level on the inside;
- Unsymmetrical loads resulting from uneven placement of backfill and/or filter pack materials;

- Uneven collapse of unstable formations;
- Sudden release of backfill materials that have temporarily bridged in the annulus;
- Weight of cement grout slurry and impact of heat of hydration of grout on the outside of a partially water-filled casing;
- Extreme drawdown inside the casing caused by over-pumping;
- Forces associated with well development that produce large differential pressures on the casing; and
- Forces associated with improper installation procedures where unusual force is used either to counteract a borehole that is not straight or to overcome buoyant forces.

Of these stresses, only external hydrostatic pressure can be predicted and calculated with accuracy; the other stresses can be avoided by common sense and good practice. To provide a sufficient margin against possible collapse by all normally-anticipated external loadings, a casing should be selected so that resistance to collapse is more than required to withstand external hydrostatic pressure alone. According to Purdin (1980), steps to minimize the possibility of collapse include:

- Drilling a straight, clean borehole;
- Uniformly distributing the filter pack materials at a slow, even rate;
- Avoiding the use of quick-setting (high temperature) cements for thermoplastic casing installation;
- Adding sand to a cement to lower the heat of hydration; and,
- Controlling negative pressures inside the casing during well development.

4.2.2 Chemical Resistance Characteristics

Monitoring well casing and screen materials should maintain their structural integrity and durability in the environment in which they are used over their operating life. Monitoring well casings and screens should be resistant to chemical and microbiological corrosion and degradation in contaminated and uncontaminated waters.

Metallic casing and screen materials are most subject to corrosion; whereas, thermoplastic casing and screen materials are most subject to chemical degradation. The extent to which these processes occur depends on water quality within the formation and changing chemical conditions such as fluctuations between oxidizing and reducing conditions. Casing materials should be chosen based on knowledge of existing and anticipated groundwater chemistry. Because subsurface conditions cannot be predicted without some preliminary sampling and analysis, the choice of appropriate well casing materials should be contingent upon preliminary water quality analyses, which will be critical to the success of a groundwater monitoring program. When water quality is unknown, it is prudent to use conservative materials (i.e., the most chemically inert materials). Cole-Parmer's online *Chemical Compatibility Database* provides general information regarding the resistance of various materials to reagent-grade chemicals.

4.2.3 Chemical Interference Characteristics

Monitoring well casing and screen materials should not chemically alter groundwater samples, especially with respect to COCs and water quality standards, due to absorption, adsorption, or leaching. If a casing material sorbs selected constituents from the groundwater, those constituents either will not be present in any water quality sample or the concentration of constituents could potentially be reduced. Additionally, if groundwater chemistry changes over time, the chemical constituents that were previously sorbed onto the casing may begin to desorb and/or leach into the groundwater. In either situation, the water quality samples are not representative.

Sorption onto casing materials or filter packs may reduce COC concentrations below quantitation limits or regulatory thresholds, resulting in: biased contaminant plume delineations; reduced sensitivity of detection; or, false-negative assessments of groundwater contamination (Palmer et al. 1987). Proper well purging may minimize the impact of sorption or leaching effects. However, purging efficiency is difficult to document. The effectiveness of purging in minimizing sorption or leaching effects of well materials depends on the relative rates and magnitudes of these processes in the borehole, filter pack, and wells—and, on the actual time of sample exposure to the materials.

In the presence of chemically reactive aqueous solutions, certain chemical constituents can be leached from casing materials. If this occurs, chemical constituents that are not indicative of formation water quality may be detected in samples collected from the well. The selection of casing material should therefore consider potential interactions between the casing material and the natural and human-induced geochemical environment. A simplified selection process to minimize chemical interaction with well casings and screens is presented in *Table 3 Recommendations regarding chemical interactions with well casings*.

With respect to well casings, there have been relatively few systematic studies of sorption and leaching, other than well-documented reports describing the persistent effects of PVC solvent cements (Sosebee et al. 1983) and the problems with corrosion of ferrous casings.

4.3 Types of Casing Materials

Casing materials widely available for use in groundwater monitoring wells can be divided into three categories:

- <u>Fluoropolymer materials</u>, including polytetrafluoroethylene (PTFE), tetrafluoroethylene (TFE), fluorinated ethylene propylene (FEP), perfluoroalkoxy (PFA), and polyvinylidene fluoride (PVDF);

- Metallic materials, including carbon steel, low-carbon steel, galvanized steel, and stainless steel (304 and 316); and
- Thermoplastic materials, including polyvinyl chloride (PVC) and acrylonitrile butadiene styrene (ABS).

In addition to these three categories that are widely used, fiberglass-reinforced plastic (FRP) has been used for monitoring applications. Because FRP has been used rarely, very little data are available on their characteristics and performance. Therefore, fiberglass-reinforced materials are not included in the following discussion.

All well construction materials possess strength-related characteristics and chemical resistance/chemical interference characteristics that influence their performance in site-specific hydrogeologic and contaminant-related monitoring situations. The characteristics for each of the three categories of materials are discussed below.

4.3.1 Fluoropolymer Materials

Fluoropolymers are synthetic materials consisting of different formulations of monomers (organic molecules) that can be molded by powder metallurgy techniques or extruded while heated. Fluoropolymers are technically included among the thermoplastics, but possess a unique set of properties that distinguish them from other thermoplastics: fluoropolymers are resistant to chemical and biological attack, oxidation, weathering, and ultraviolet radiation; they have a broad useful temperature range (up to 550^{o}F) and a high dielectric constant; they exhibit a low coefficient of friction; they have anti-stick properties; and they possess a greater coefficient of thermal expansion than most other plastics and metals.

A variety of fluoropolymer materials are marketed under a number of different trademarks. Polytetrafluoroethylene (PTFE) was discovered by E. I. Du Pont de Nemours in 1938. PTFE's properties include an extreme temperature range (from -400^{o}F to +550^{o}F in constant service) and the lowest coefficient of friction of any solid material (Hamilton 1985). PTFE is by far the most widely-used and produced fluoropolymer. Fluorinated ethylene propylene (FEP) was also developed by E. I. Du Pont de Nemours and is perhaps the second most widely used fluoropolymer. It duplicates nearly all of the physical properties of PTFE except the upper temperature range, which is 100^{o}F lower. Production of FEP-finished products is generally faster because FEP is melt-processable, but raw material costs are higher. Perfluoroalkoxy (PFA) combines the best properties of PTFE and FEP, but PFA costs substantially more than either PTFE or FEP. Polyvinylidene fluoride (PVDF) is tougher and has a higher abrasion resistance than other fluoropolymers, and is resistant to radioactive environments. PVDF also has a lower maximum temperature limit than either PTFE or PFA.

Care should be exercised in the use of trade names to identify fluoropolymers. Some manufacturers use one trade name to refer to several of their own different materials. For example, DuPont refers to several of its fluorocarbon resins as Teflon®, although the actual products have different physical properties and different fabricating techniques. These materials may not always be interchangeable in service or performance.

Aller et al. (1989) provides an excellent summary of the research on PTFE materials performed by Hamilton (1985), Reynolds and Gillham (1985), Barcelona et al. (1985a), Barcelona et al. (1985b), Dablow et al. (1988), and Lang et al. (1989). The following advantages and disadvantages of PTFE are highlighted in Aller et al.'s (1989) summary and by Nielsen (2006).

Advantages of PTFE well casing and screen materials:

- Can be used under a wide range of temperatures; and
- Fairly easily machined, molded, or extruded.

Disadvantages of PTFE well casing and screen materials:

- May adsorb/desorb organic constituents from/into solution;
- Only slotted casing is available for screens;
- Ductile behavior of PTFE ("creep" or "cold flow") may result in the partial closing of screen slots;
- PTFE's extreme flexibility may result in non-plumb and bowed wells;
- Non-stick nature of PTFE may cause annular seal failure;
- Moderate weight and low strength per unit length; and
- PTFE casing and screen is unsuitable for driven wells.

Emerging COCs include various PFCs, which are persistent, bioaccumulative, toxic, and ubiquitous in the environment (WWF 2014). PFCs, which provide heat stability and non-stick properties, may be associated with PTFE as impurities or breakdown products (e.g., perfluorooctane sulfonate [PFOS] and perfluorooctanoic acid [PFOA]). PTFE well materials may not be appropriate for sites where COCs include PFCs (e.g., on sites where fire-fighting foams were used). Research on these compounds is ongoing.

Structural strength of screen materials is primarily a problem only with PTFE screen materials, which are affected by a phenomenon known as "creep" or "cold flow". Under constant stress through time, such as continuous loading of the entire length of casing, PTFE can deform plastically (i.e., it retains the deformed shape after the stress is removed), and in screened casings made of PTFE, the result can be partial or complete closure of the slots, thus effectively ruining the well's usefulness for monitoring purposes. This is a problem, however, only when the wells are relatively deep (250 feet or deeper); in shallow wells the physical resistance of PTFE to compression is greater than is its tendency to deform plastically (DuPont, reference 1).

If PTFE is to be used in deeper wells, structural strength problems can be avoided by using slightly larger slots; larger slots may be narrowed slightly because of cold flow, however they will not be completely sealed shut. It may also be possible to obtain PTFE casing that has been modified by the use of fillers. Fillers can be used to increase the resistance to cold flow by approximately a factor of 2 (Du Pont, reference 1), thus limiting the deformation that will occur in the screened casing. More information about "cold flow" phenomena is available from the manufacturer (Du Pont, reference 2).

4.3.2 Metallic Materials

Metallic well casing and screen materials available for use in monitoring wells include carbon steel, low carbon steel, galvanized steel, and stainless steel. Well casings and screens made of any of these metallic materials are generally stronger, more rigid, and less temperature sensitive than thermoplastic, fluoropolymer, or fiberglass-reinforced epoxy casing materials. The strength and rigidity of metallic casing materials are sufficient to withstand virtually any subsurface condition encountered in a groundwater monitoring situation, but metallic materials may be subject to corrosion during long-term exposure in certain subsurface geochemical environments.

Corrosion is defined as the weakening or destruction of a material by chemical action. Corrosion of metallic well casings and well intakes can both limit the useful life of the monitoring well installation and result in groundwater sample analytical bias. It is important, therefore, to select both casing and screen that are made from corrosion-resistant materials.

Several well-defined forms of corrosive attack on metallic materials have been observed and defined. In all forms, corrosion proceeds by electrochemical action, and water in contact with the metal is an essential factor. According to Driscoll (1986), the forms of corrosion typical in environments where well casing and well intake materials are installed include:

1) General oxidation or "rusting" of the metallic surface, resulting in uniform destruction of the surface with occasional perforation in some areas;

2) Selective corrosion or loss of one element of an alloy (e.g., dezincification), leaving a structurally weakened material;

3) Bi-metallic corrosion, caused by the creation of a galvanic cell at or near the juncture of two different metals;

4) Pitting corrosion, or highly localized corrosion by pitting or perforation, with little loss of metal outside of these areas; and

5) Stress corrosion, or corrosion induced in areas where the metal is highly stressed.

To determine the potential for corrosion of metallic materials, the natural geochemical conditions should first be determined. The following list of indicators can help recognize potentially corrosive conditions (modified from Driscoll 1986).

1) Low pH. If groundwater pH is less than 7.0, water is acidic and corrosive conditions exist.

2) High dissolved oxygen content. If dissolved oxygen content exceeds 2 milligrams per liter: corrosive water is indicated.

3) Presence of hydrogen sulfide (H_2S). H_2S in quantities as low as 1 milligram per liter can cause severe corrosion.

4) Total dissolved solids (TDS). If TDS is greater than 1,000 milligrams per liter, the electrical conductivity of the water is great enough to cause serious electrolytic corrosion.

5) Carbon dioxide (CO_2). Corrosion is likely if the CO_2 content of the water exceeds 50 milligrams per liter.

6) Chloride (Cl^-), bromide (Br^-), and fluoride (F^-) content. If Cl^-, Br^-, and F^- concentrations together exceed 500 milligrams per liter, corrosion can be expected.

Combinations of any of these corrosive conditions generally increase the corrosive effect.

Carbon steels were produced primarily to provide increased resistance to atmospheric corrosion. Achieving this increased resistance requires that the material be subjected to alternately wet and dry conditions. In most monitoring wells, water fluctuations are not sufficient in either duration or occurrence to provide the conditions that minimize corrosion. Therefore, the difference between the corrosion resistance of carbon and low-carbon steels in the unsaturated or in the saturated zone is negligible, and both materials may be expected to corrode approximately equally.

Corrosion products may precipitate in the filter pack, well screen, or surrounding formation—or be released to the groundwater.

Corrosion products of carbon and low-carbon steel include iron, manganese, and trace metal oxides as well as various metal sulfides (Barcelona et al. 1983). Under oxidizing conditions, the principal products are solid hydrous metal oxides; under reducing conditions, high concentrations of dissolved metallic corrosion products can be expected (Barcelona et al. 1983). While the electroplating process of galvanizing improves the corrosion resistance of either carbon or low-carbon steel, in many subsurface environments the improvement is only slight and short-term. The products of corrosion of galvanized steel include iron, manganese, zinc, and traces of cadmium (Barcelona et al. 1983).

The surfaces where corrosion occurs present potential locations for adsorption and for a variety of chemical reactions. These surface interactions can cause significant changes in dissolved metal or organic compounds in groundwater samples (Marsh and

Lloyd 1980). According to Barcelona et al. (1983), even purging the well prior to sampling may not be sufficient to minimize this source of sample bias because the effects of the disturbance of surface coatings or accumulated corrosion products in the bottom of the well are difficult, if not impossible, to predict. On the basis of these observations, the use of carbon steel, low-carbon steel, and galvanized steel in monitoring well construction is not recommended in most natural geochemical environments.

Conversely, stainless steel performs well in most corrosive environments, particularly under oxidizing conditions. In fact, stainless steel requires exposure to oxygen to attain its highest corrosion resistance; oxygen combines with part of the stainless steel alloy to form an invisible protective film on the surface of the metal. As long as the film remains intact, the corrosion resistance of stainless steel is high. However, long-term exposure of stainless steel to corrosive conditions may result in corrosion and the subsequent contamination of groundwater samples by chromium or nickel. Barcelona and Helfrich (1988) and Barcelona et al. (1988a) suggest that biological activity may alter geochemistry near stainless steel wells. Iron bacteria may induce degradation of the well casing and screen.

Several different types of stainless steel alloys are available. The most common alloys used for well casing and screen are Type 304 and Type 316. Type 304 stainless steel is perhaps the most practical from a corrosion resistance and cost standpoint. It is composed of 18%-20% chromium, 8%-12% nickel, and not more than 0.08% carbon. Chromium and nickel give the 304 alloy excellent resistance to corrosion; the low carbon content improves weldability. Type 316 stainless steel is compositionally similar to Type 304 except that Type 316 has 2%-3% molybdenum and a 10%-14% nickel. This compositional difference provides Type 316 stainless steel with an improved resistance to sulfur-containing compounds and sulfuric acid solutions (Barcelona et al. 1983). Type 316 generally performs better than Type 304 under reducing conditions. According to Barcelona et al. (1983), Type 316 stainless steel is less susceptible to pitting or pinhole corrosion caused by organic acids or halide solutions.

The following advantages and disadvantages of stainless steel are highlighted by Aller et al. (1989) and by Nielsen (2006):

Advantages of stainless steel well casing and screen materials:

- High strength in wide range of temperatures;
- Readily available;
- High open area screens available; and,
- Suitable for driven wells.

Disadvantages of stainless steel well casing and screen materials:

- May corrode under some geochemical and microbiological conditions;

- May contribute metal ions (i.e., iron, chromium, nickel, manganese, and molybdenum) to groundwater samples; and,
- High weight per unit length.

4.3.3 Thermoplastic Materials

Thermoplastic materials are man-made and are composed of different formulations of large organic molecules. These formulations soften by heating and harden upon cooling, and therefore, can be easily molded or extruded into a wide variety of useful shapes including well casings, screens, fittings and accessories. The most common types of thermoplastic well casing and screen are PVC and ABS.

PVC plastics are produced by combining PVC resin with various types of stabilizers, lubricants, pigments, fillers, plasticizers, and processing aids. The amounts of these additives can be varied to produce different PVC plastics with properties tailored to specific applications.

PVC materials are classified according to ASTM (2012b) that covers rigid PVC compounds. This standard categorizes rigid PVC by numbered cells designating value ranges for certain pertinent properties and characteristics, including: impact strength, tensile strength, rigidity (modulus of elasticity), temperature resistance (deflection temperature), and chemical resistance. ASTM (2014) covers thermoplastic water well casing pipe and couplings made in standard dimension ratios. This standard specifies that PVC well casing can be made from only a limited number of cell classification materials, predominantly PVC 12454-B, but also including PVC 12454-C and PVC 14333-C and D.

ABS plastics are produced from three different monomers: 1) acrylonitrile, 2) butadiene, and 3) styrene. The ratio of the components and the way that they are combined can be varied to produce plastics with a wide range of properties. Acrylonitrile contributes rigidity, impact strength, hardness, chemical resistance, and heat resistance. Butadiene contributes impact strength. Styrene contributes rigidity, gloss, and ease of manufacturing (National Water Well Association and Plastic Pipe Institute 1981). The ABS used for well casing is a rigid, strong unplasticized polymer formulation that has good heat resistance and impact strength.

Two ABS material types are used for well casings: 1) a higher strength, high rigidity, moderate impact resistance ABS and 2) a lower strength and rigidity, high impact strength ABS. These two materials are identified as cell class 434 and 533, respectively, by ASTM (2014). High temperature resistance and the ability of ABS to better retain other properties at high temperatures are advantages in wells where grouting with cement results in high temperature caused by the cement's heat of hydration.

Aller et al. (1989) describes some of the research that has been performed regarding degradation of thermoplastic materials and the adsorption/desorption of contaminants onto/from various thermoplastic materials. The potential sources of chemical interference from thermoplastic well casing materials, either from desorption or chemical degradation, are: 1) the basic monomers from which the casing is made (e.g., vinyl chloride monomer) and 2) a variety of additives that may be used in the manufacture of the casing including: plasticizers, stabilizers (e.g., PVC heat-stabilizing compounds such as dimethyl tin and dibutyl tin), fillers, pigments, and lubricants. The significance and impact of these sources of chemical interference is not currently known, and may vary based on site-specific conditions.

With respect to chemical interference effects, Aller et al. (1989) explains that another potential area of concern is the possibility that some chemicals could be sorbed by PVC well casing materials. Studies regarding sorption of chemical species onto PVC are inconclusive with respect to both the significance of contaminant sorption by PVC and the ability of well purging to correct any sample interferences.

The following advantages and disadvantages of PVC materials are highlighted in Aller et al.'s (1989) discussion and by Nielsen (2006).

Advantages of PVC well casing and screen materials:

- Completely resistant to galvanic and electrochemical corrosion;
- Light weight for ease of installation;
- High abrasion resistance;
- Requires low maintenance;
- Flexible and workable for ease of cutting and joining;
- High strength and low weight per unit length;
- Readily available; and,
- High open area screens available.

Disadvantages of PVC well casing and screen materials:

- May degrade in high concentrations of certain organic solvents, especially low molecular weight ketones, amines, aldehydes, and chlorinated alkenes and alkanes (Barcelona et al. 1983);

- May fail if subjected to high differential pressures (i.e., during surging); weaker and less rigid than metallic casing materials;

- May fail if subjected to high temperatures (i.e., during grouting with neat cement);

- Long-term exposures of some formulations of thermoplastic materials to the ultraviolet radiation of direct sunlight (e.g., above-ground portions of casings) and/or to low temperatures may cause brittleness and gradual loss of impact strength that may be significant; and,

- Unsuitable for driven wells.

The National Sanitation Foundation (NSF) has set specifications for certain chemical constituents in PVC formulations. The purpose of these specifications as outlined in NSF Standard 14 (NSF 2012) is to control the amount of chemical additives in both PVC well casing and pipe used for potable water supply. Most of the maximum contaminant levels correspond to those set by the *Safe Drinking Water Act* for chemical constituents covered by the national Interim Primary Drinking Water Standards. Only PVC products that carry either the "NSF wc" (well casing) or "NSF pw" (potable water) designation have met the specifications set forth in Standard 14. Other non-NSF listed products may contain chemical additives not addressed by the specifications, or may contain concentrations of the listed chemicals that are higher than permitted by the specifications. In all cases, the material used should have been demonstrated to be compatible with the specific applications. For example, even though neither lead nor cadmium has been permitted as a compounding ingredient in United States-manufactured NSF-listed PVC well casing since 1970, PVC manufactured in other countries may be stabilized with lead or cadmium compounds that may leach from the PVC (Barcelona et al. 1983).

4.3.4 Composite Alternative Materials

In certain conditions it may be advantageous to design a well using more than one material for well components. For example, where stainless steel or fluoropolymer materials are preferred in a specific chemical environment, costs may be saved by using PVC in non-critical portions of the well. These savings may be considerable, especially in deep wells where only the lower portion of the well has a critical chemical environment and tens of feet of lower-cost PVC may be used in the upper portion of the well. In a composite well design, dissimilar metallic components should not be used unless an electrically isolating design is incorporated (i.e., a dielectric coupling) (USEPA 1986).

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FIGURES

Figure 1 Typical Monitoring Well

(with Above-Ground Surface Completion)

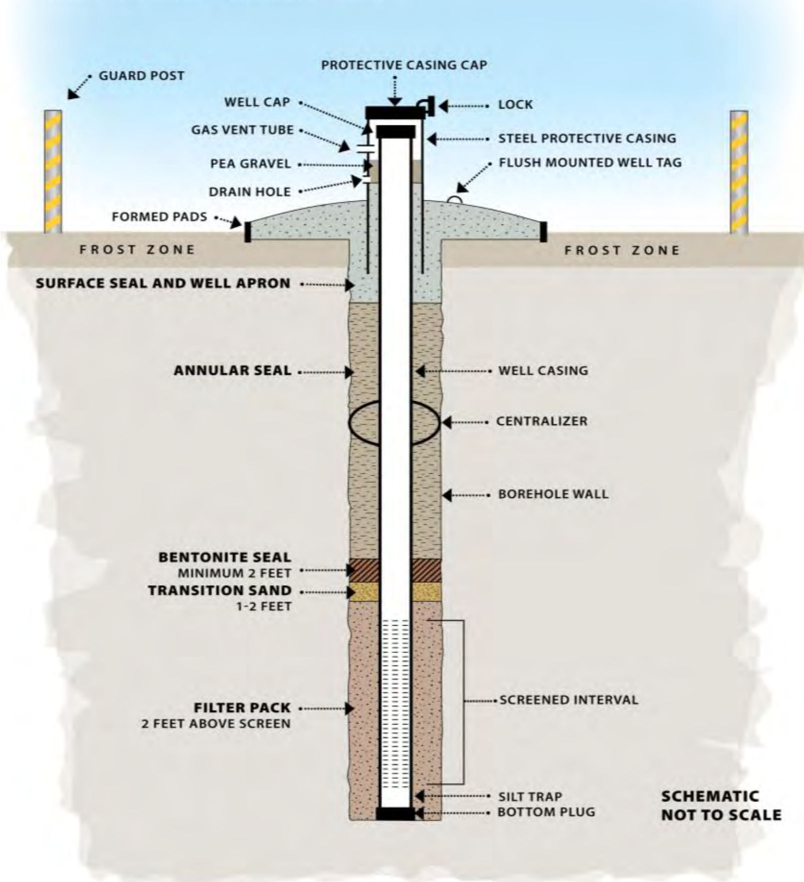

Figure 2: Multi-Level System, Nested Wells, and Well Cluster

(with Above-Ground Surface Completions)

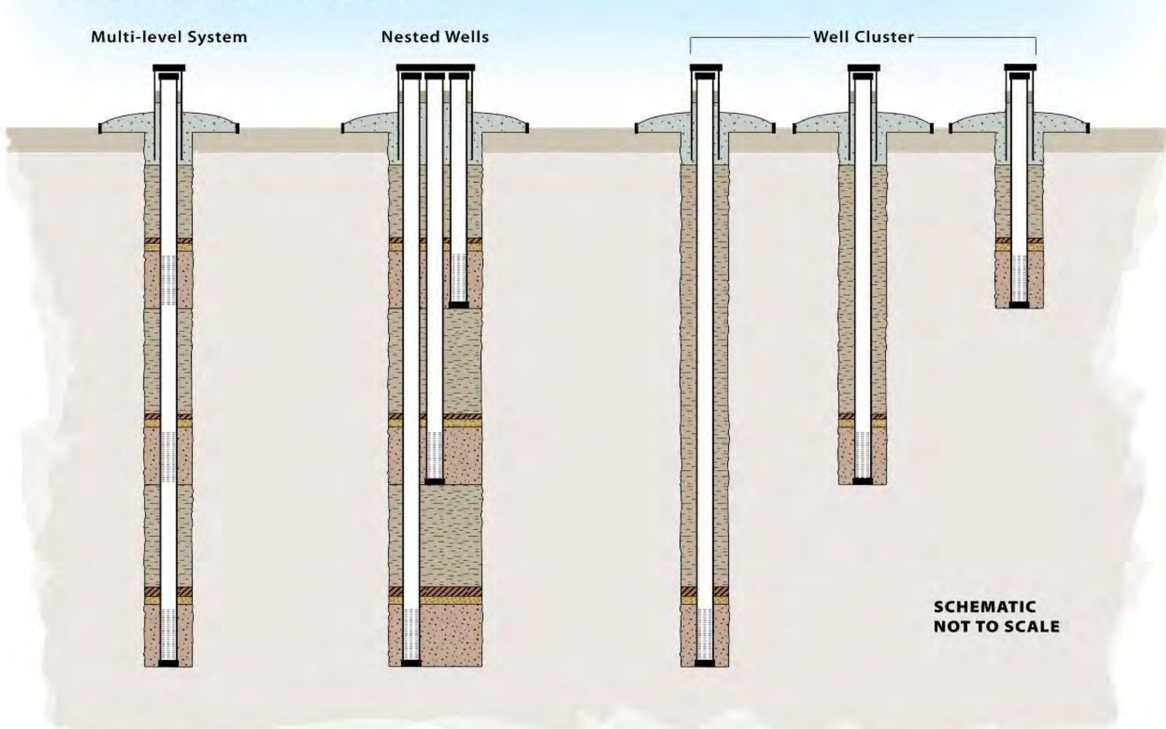

Table 1. General recommendations for selection of well casing and screen materials
From USEPA (1992)

	Do Not Use:	Use:
1.	PTFE if well depth exceeds 225 - 375 feet (68.6 - 14 meters)	PVC, ABS, SS
2.	PVC or ABS if well depth exceeds 1200 - 2000 feet (366 - 610 meters)	SS
3.	SS if pH < 7.0	PVC, ABS or PTFE
4.	SS if D.O. > 2 ppm	PVC, ABS or PTFE
5.	SS if H_2S > 1 ppm	PVC, ABS or PTFE
6.	SS if TDS > 1000 ppm	PVC, ABS or PTFE
7.	SS if CO_2 > 50 ppm	PVC, ABS or PTFE
8.	SS if Cl^- > 500 ppm	PVC, ABS or PTFE
9.	PVC if a neat PVC solvent/softening agent* is present or if the aqueous concentration of the PVC solvent/softening agent exceeds 0.25 times Its solubility in water	SS, PTFE
10.	Solvent-bonded joints for PVC casings	Threaded PVC casings
11.	Welding stainless joints	Threaded SS casings
12.	Any PVC well casing that is not NSF-ASTM approved – D-1785 and F-480	NSF-ASTM approved PVC well Casings – D-1785 and F-480
13.	Any stainless steel casing that is not ASTM approved – A312	ASTM approved SS 304 and SS 316 casings – A312
14.	Any ABS well casing that is not ASTM approved	ASTM approved ABS casings – F-480

*Known PVC solvents/softening agents include:
Tetrohydrofuran, cyclohexane, methyl ethyl ketone, methyl isobutyl ketone, methylene chloride, trichloromethane, 1,1-dichloroethane, 1,1,1-trichloroethane, trichloroethylene, benzene, toluene, acetone, and tetrachloroethylene.

ABS Acrylonitrile butadiene styrene
D.O. Dissolved oxygen
ppm parts per million
PTFE Polytetrafluoroethylene
PVC Polyvinyl chloride
SS Stainless steel
TDS Total dissolved solids

Table 2. Comparative strengths of well casing materials
From USEPA (1992)

	Casing Tensile Strength (lb)		Casing Collapse Strength (lb/In^2)	
Material	2-inch diameter nominal	4-inch diameter nominal	2-inch diameter nominal	4-inch diameter nominal
Polyvinyl chloride (PVC)	7,500	22,000	307	158
PVC casing joint[b]	2,800	6,050	300	150
Stainless steel (SS)[c]	37,760	92,000	896	315
SS casing joint[b]	15,900	81,750	No data	No data
Polytetrafluoroethylene (PTFE)	3,800	No data	No data	No data
PTFE casing joints[b]	540	1,890	No data	No data
Epoxy fiberglass	22,600	56,500	330	250
Epoxy casing joints[d]	14,000	30,000	230	150
Acrylonitrile butadiene styrene (ABS)	8,830	22,000	No data	No data
ABS casing joints[d]	3,360	5,600	No data	No data

[a] Information provided by E. I. du Pont de Nemours & Company, Wilmington, DE.

[b] All joints are flush-threaded.

[c] Stainless steel casing materials are Schedule 5 with Schedule 40 joints; other casing materials (PVC, PTFE, epoxy, ABS) are Schedule 40.

[d] Joints are not flush-threaded, but are a special type that is thicker than Schedule 40.

Table 3. Recommendations regarding chemical interactions with well casings
From USEPA (1992)

If Monitoring for:	Best Choices 1st Choice	Best Choices 2nd Choice	Avoid If Possible
Metals	PTFE	PVC	SS 304 & SS 316[+]
Organics	SS 304 & SS 316	PVC*	Galvanized Steel and PTFE**
Metals & Organics	None	PVC & PTFE	SS 304 & SS 316

[+] Substantial concentrations of metals can be leached from SS if the contact time is 2 hours or longer.

* PVC is acceptable if free product is not present and concentrations are less than ~.25 solubility (Ohio 2008).

** Do not use PTFE for monitoring VOCs (see list on Table 1). PTFE tends to be more sorptive of organics than PVC. Hydrophobic organics (Log Kow $\geq$ ~2) are most readily sorbed.

ABS Acrylonitrile butadiene styrene
Kow Octanol-water partition coefficient
PTFE Polytetrafluoroethylene
PVC Polyvinyl chloride
SS Stainless steel
VOC Volatile organic compound

GLOSSARY

Aquifer. A geologic formation of relatively high permeability that allows water to move through it. A well in an aquifer produces a usable quantity of water.

Annular space or well annulus. The space between the borehole wall and the well casing, or between two well casings.

Borehole. An open or uncased subsurface hole created by a drilling device.

Centralizer. A device attached to the well casing which serves to center the well within the borehole.

Piezometer. A small-diameter well having a very short well screen used to measure piezometric pressure or hydraulic head in an aquifer or water-bearing zone.

Screened interval. The section of well screen that permits fluids or vapors to pass through.

Tremie pipe. A small-diameter pipe used to deliver the sand filter pack and other well sealing materials into the annular space. Annular materials are placed in the well by setting the end of the tremie pipe at the bottom of the borehole and then moving it upward.

Turbidity. A measurement of the relative clarity of a liquid, based on optical characteristics.

Well purging. A procedure that removes water and fine-grained materials from the well prior to collecting a representative water sample from a groundwater formation.

Well screen. The portion of the well casing that has slots or holes of uniform width, orientation, and spacing which permits fluids or vapors to pass through.