2. Site Challenges

Develop a Conceptual Site Model Based on Site Challenges

Remediation is inherently difficult—even at simple sites. Complex sites, however, have both technical and nontechnical challenges that can prevent remedial approaches from meeting site objectives or transitioning to long-term management within a reasonable time frame. CSMs traditionally focus on the technical aspects of a site and thus may not include the nontechnical issues, such as future land use or stakeholder concerns, that can create additional complexity for a site. If substantial complexities are identified, a remediation potential assessment is recommended to address the question of whether adaptive site management is warranted (see Figure 1).

2.1 Technical Challenges

Table 2 includes many, but not all, of the technical challenges that can result in a complex site.

Table 2. Technical challenges of complex sites

Technical Challenges	Examples
Geologic conditions	• Geologic heterogeneity/preferential flow paths • Faults • Fractured bedrock • Karst geology • Low-permeability media
Hydrogeologic conditions	• Extreme or variable groundwater velocities • Fluctuating groundwater levels • Deep groundwater contamination • Surface water and groundwater interactions and impacted sediment
Geochemical conditions	• Extreme geochemistry (such as unusually high or low pH or alkalinity, elevated electron acceptors, extreme redox conditions) • Extreme groundwater temperatures
Contaminant-related conditions	• Light or dense nonaqueous phase liquids (LNAPL or DNAPL) • Recalcitrant contaminants • High contaminant concentrations or multiple contaminants • Emerging contaminants
Large-scale site	• Location and extent of contamination • Number, type and proximity of receptors • Depth of contamination • Extensive or comingled plumes

Go to section 2.2 Nontechnical Challenges

Each of the technical challenges listed in Table 2 is described in more detail in the following subsections. The adequacy of characterization is important for each of these factors. ITRC has previously published guidance on the selection of site characterization tools that may be useful at complex sites (see for example, ITRC 2015b).

Framework for Selecting Investigative Tools and Analyses

ITRC (2015b) provides examples of how to implement site characterization tools, such as integrated site *characterization (ISC), for different types of sites and objectives. To help identify applicable tools, ITRC also provides a Tools Selection Worksheet for the interactive selection of over 100 tools based on geologic, hydrologic, and chemical data needs at a site. The Tool Selection Worksheet is linked to more detailed descriptions of each tool—including its applicability, data quality capability, and limitations or challenges. Examples of tools listed in the worksheet include sampling and analysis methods, chemical screening methods, geochemical characterization tools, environmental molecular diagnostics, microbial diagnostics, hydraulic testing, tracer tests, geophysics and more. In addition to investigative tools, plume migration and contaminant transport can be analyzed and predicted using simple graphical techniques, modeling, or 3D visualization software.*

2.1.1 Geologic Conditions

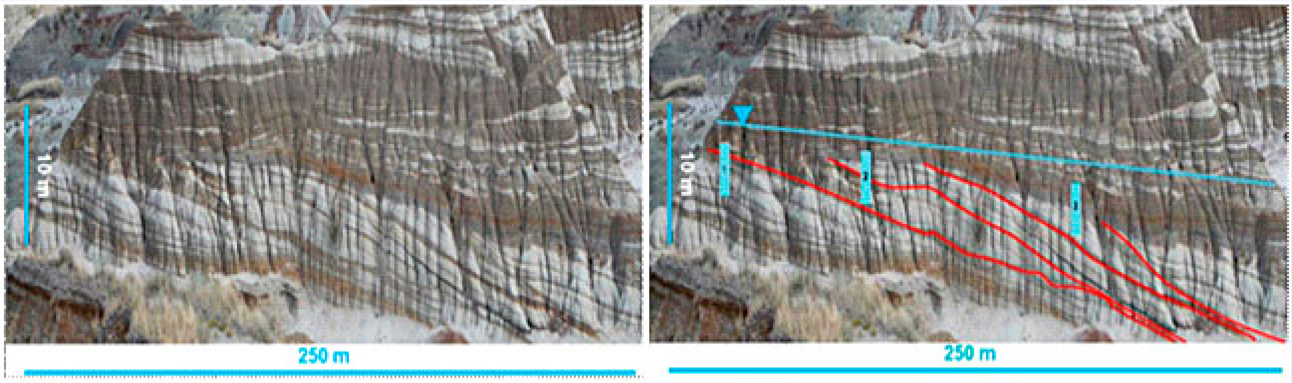
Complex geology at a site can lead to technical challenges when designing an effective remediation approach. Geologic conditions may complicate the development of a CSM, the selection of an appropriate remediation approach, and the time frame needed to meet site objectives. Complicating conditions can include geologic heterogeneity, fractured bedrock, karst geology, and low-permeability media—all of which can control contaminant migration because the geology forms the "plumbing" that influences fluid flow and contaminant transport in the subsurface. The geology thus determines contaminant migration pathways, the nature and extent of contamination, and contaminant transport and storage zones, which must be included in a representative subsurface CSM. Understanding the site geologic conditions is also critical for the subsequent analysis of hydrogeology and chemistry data sets.

2.1.1.1 Geologic Heterogeneity/Preferential Flow Paths

The heterogeneity of the aquifer matrix can control contaminant migration; see *Integrated DNAPL Site Strategy* (ITRC 2011b) for detailed information on this topic. Varied stratigraphy can result in intermittent contamination that complicates characterization (USEPA 2016a). For instance, fluvial systems often produce interlayered clastic sedimentary deposits, in which higher permeability coarse-grained (sand/gravel) channel deposits are encased in lower permeability (silt/clay) floodplain deposits. Groundwater and related contaminants preferentially migrate through the more permeable channel deposits. Permafrost areas in northern regions may also create preferential flow paths (thaw channels) where intermittent melting has occurred or where discontinuous lenses occur. This preferential flow can be exacerbated when contaminants accumulate in less permeable zones because of the concentration gradients. These zones then serve as secondary sources of contamination via matrix diffusion back into the more permeable zones. Other primary and secondary sedimentary features can also affect groundwater pathways, making it difficult to anticipate and follow contaminant migration (USEPA 2016a).

Complex Sites and the Value of Accurate Subsurface Characterization

The photos below illustrate a significant challenge to successful groundwater remediation: stratigraphic heterogeneity. This geological heterogeneity results from stratigraphic layering and is common at groundwater remediation sites where sedimentary aquifers are affected. Unfortunately, also common is the practice of "layer cake" designations of aquifers, in which it is assumed that the first sand encountered when drilling is a homogeneous, isotropic layer, followed by the next layer, and so on. At complex, heterogeneous sites this configuration is seldom present. In the example presented here, lateral shifting of the river channel through time has caused the sands to be deposited not from the bottom up (as commonly assumed), but rather from left to right as the channel migrated with time. In this meandering river deposit, clay units (dark colored) in the outcrop (Upper Cretaceous, Alberta, Canada) separate laterally offset-stacked, or shingled, sand units (point bar deposits, light colored). The right photo highlights clay units dipping from upper left to bottom right (red lines).



Blue rectangles indicate hypothetical well screens. Interwell communication is severely limited due to stratigraphic dip. The three hypothetical wells shown installed into the uppermost sand for monitoring or remediation are not in hydraulic communication with one another. High resolution subsurface data at these locations would look similar, and the lateral shingling would not be identified without knowledge of the depositional environment and stratigraphy. Depositional models, or facies models, predict such heterogeneity and should be applied at groundwater remediation sites where sedimentary aquifers are affected (Photo courtesy of Hubbard 2015).

Mapping the heterogeneities can be helpful for determining the nature and extent of contamination, contaminant migration pathways, and contaminant transport and storage zones at complex sites. *Integrated DNAPL Site Characterization* (ITRC 2015b) provides methodologies for characterizing heterogeneous geologic features at complex sites.

2.1.1.2 Fractured Bedrock

Fractured bedrock aquifers can also be difficult to remediate. Groundwater flow and contaminant transport in fractured bedrock aquifers are typically dominated by secondary fracture porosity, with matrix diffusion of contaminants into and out of primary porosity significantly affecting contaminant flow and distribution (ITRC 2011b, NRC 2005). Because the hydraulic conductivity of the fracture zone is normally quite high, this secondary porosity is often the dominant pathway for rapid fluid flow in highly heterogeneous fractured rocks. It is extremely challenging to map out the fracture occurrence and nature and extent of groundwater contamination to the degree necessary to design an effective contaminant monitoring program and remediation system. This topic is addressed in ITRC's *Characterization and Remediation of Fractured Bedrock* guidance (ITRC 2017a).

Case Study: UGI Columbia Gas Plant Site

The UGI Columbia Gas Plant Superfund site is located on less than an acre of a much larger industrial area of Pennsylvania near the Susquehanna River. A century of manufacturing gas products at the site has left volatile organic compounds (VOCs), polyaromatic hydrocarbons (PAHs), heavy metals, and cyanide in soil, sediments, groundwater, and surface waters. Residual DNAPL in overburden and shallow and deep fractured bedrock (to a depth of 160 feet) significantly affected the remedial approach. Remediation for this complex site includes on-site capping, institutional controls, industrial site use restrictions, interim actions, and a technical impracticability waiver. More details are presented in the full case study.

2.1.1.3 Karst Geology

Karst topography forms when the soluble areas of sedimentary bedrock dissolve, leaving cavities that range from small voids to large caverns. Groundwater transport, permeability and flow velocities through these cavities can be orders of magnitude higher than in other bedrock settings, and contaminants can travel long distances with little dilution in karst, as compared to granular porous media aquifers (NRC 2013). Networks of karst conduits are also highly variable, resulting in unpredictable groundwater migratory pathways that are ill-suited to conventional monitoring techniques such as monitoring wells.

Further complicating this geology, shallow karst geology systems are often well connected to surface waters. Because of this connection, groundwater and contaminant mass discharges to perennial or temporal streams, springs, and other surface water bodies are often highly responsive to precipitation. Sinkholes and conical depressions in the ground surface may result. Tracer tests can aid in the characterization and remedial design for karst geology settings (ITRC 2015b).

2.1.1.4 Low-Permeability Media

Contaminants in low-permeability areas of the subsurface diffuse back into higher permeability zones once concentrations in the higher zones decrease. Thus, back-diffusion from low-permeability media can sustain contaminant plumes in higher permeability zones long after the contaminant source is gone (ITRC 2011b). This situation should be evaluated on a site-specific basis, as heterogeneous and anisotropic conditions at a site may complicate the CSM and lead to erroneous conclusions.

Contamination that exists in low-permeability zones may still require extended remediation time frames even when remediation additives are injected (for example, injection of permanganate or adding engineered microorganisms). These additives do not contact the contaminants until they have diffused into the more permeable zones. Fluxes from low-permeability to higher-permeability zones can keep pump-and-treat (P&T) systems operating inefficiently, depending on the rate of diffusion, for decades.

2.1.2 Hydrogeologic Conditions

CSMs that assume homogenous and isotropic flow conditions can over-simplify aquifer analysis. These simplistic assumptions often do not reflect actual heterogeneous and anisotropic conditions and may cause an incomplete or incorrect CSM to be developed. Some of the specific hydrogeologic conditions that can make a site difficult to characterize and remediate include variable groundwater velocities, groundwater levels that fluctuate due to various local conditions, deep groundwater aquifers, and groundwater/surface water interactions. These conditions are described more fully in the subsections below.

2.1.2.1 Extreme or Variable Groundwater Velocities

Low groundwater velocities often increase the time frame to reach site objectives. In addition, slow-moving groundwater also provides greater contact time for contaminants to adsorb to the aquifer solids. On the other hand, as with karst geology, high groundwater velocities may prevent adequate reductions in contaminant concentrations. Other factors may influence changes in groundwater velocity, such as changes in recharge. In addition, portions of an aquifer may discharge in specific areas, causing localized changes in gradients and velocities (magnitude and possibly direction), compared with the rest of the aquifer.

2.1.2.2 Fluctuating Groundwater Levels

Groundwater levels typically fluctuate because of different influences, including:

- tidal changes in coastal areas
- changes due to barometric pressure
- increased or decreased recharge (often seasonal)
- changes in river stage
- changes in water usage

Water level fluctuations are typically determined during long-term monitoring programs. Changing water levels at some sites can complicate site characterization. Flow directions may change as the water levels move up and down, causing unusual plume migration patterns. The flow direction may change permanently due to changes in water usage. Rising water levels may also inundate LNAPL, trapping it beneath the water table and making it difficult to remove.

Case Study: Velsicol Site, St. Louis, Michigan

Chemical plant operations at the Velsicol site contaminated subsurface groundwater, including the city's well field, and the nearby Pine River. DNAPL pools were detected 100 feet below ground surface in semi- to low- permeability fractured till units that transition to sands and gravels of the aquifer system. The semiconfining unit under the site was assumed to be an impermeable clay unit when a circumferential slurry wall remedy was constructed to prevent contaminants from migrating. The remedy failed, however, due to poor keying of the slurry wall and leakage through the low-permeability fractured till unit.

In the fall of 2015, the city shut down the contaminated regional aquifer well field, which had operated since the early 1900s and began operating a new, replacement well field. Although the regional aquifer had been artesian prior to well field operation in the 1900s, it was assumed that regional agriculture and other uses would prevent artesian conditions from being reestablished. Within several months of shutting down the well field, however, artesian flow conditions developed at observation wells and city water supply wells. Domestic wells beyond the city limits flooded basements and left front yards saturated. More details are presented in the full case study.

2.1.2.3 Deep Groundwater Contamination

Characterizing contaminant distribution and transport in deep aquifers is usually complicated by the scarcity of direct data, which can be limited by the cost and difficulty of deep boreholes. Characterization is often on a regional scale and increasingly uses geophysical methods borrowed from the oil and gas industry. Several surface geophysical methods can be used to image the structure of deep aquifers and estimate the water quality (Jansen 2014). While many of the most common methods are limited to a few hundred feet in depth, some methods can characterize aquifers to depths of several thousand feet. Deep groundwater methods include time domain electromagnetic induction (TEM), magnetotellurics (MT), seismic reflection, and gravity measurements. These methods can be used to map aquifers, find faults and fractures, map saline water, estimate lithology, and detect facies changes within an aquifer. Designing and implementing an effective remedial system for deep groundwater is therefore costly and difficult.

2.1.2.4 Surface Water and Groundwater Interactions and Impacted Sediments

The interactions between groundwater and surface water can be complex even in the absence of contamination. These interactions can be influenced by climate, topography, geology, and human activity such as groundwater withdrawal or flood control measures. Recharge and discharge processes, along with biotic and abiotic chemical processes within the upper layer of sediments beneath surface water (hyporheic zone), can cause changes to the chemistry of the interchanged water. Furthermore, sediment transport and deposition varies spatially over time and is often challenging to model.

A multidisciplinary approach may be required to characterize the key groundwater hydrogeology, surface water hydrology, chemistry, and biological aspects driving the interactions. Investigation and remediation equipment and techniques deployed in aquatic settings are more specialized and complex than those used in terrestrial settings. The presence of contamination in an aquatic environment also introduces additional potential human and ecological receptors. The regulatory framework for a site with surface water and sediment contamination can also become more complex because site management and remediation activities often encompass multiple laws and regulations (for example, CERCLA and the Clean Water Act), agencies (such as states and tribes, USEPA, Army Corps of Engineers, U.S. Coast Guard) or even multiple programs within agencies (such as remediation and water programs).

Several references for more information on surface water and groundwater interactions and impacted sediments include the following:

- *Ground Water and Surface Water, A Single Resource* (Winter et al. 1998)
- *Proceedings of the Ground-Water/Surface-Water Interactions Workshop, Solid Waste and Emergency Response* (USEPA 2000)
- *Contaminated Sediment Remediation Guidance for Hazardous Waste Sites* (USEPA 2005a)
- *Characterization of Contaminated Ground Water Discharge to Surface Water Technical Guidance, Version 1.0* (NJDEP 2016)
- *Guidance on Evaluating Sediment Contaminant Results* (Ohio EPA 2010)

2.1.3 Geochemical Conditions

The geochemistry encountered in soil and groundwater is unique for every site. Differences in soil mineralogy, groundwater composition, and naturally occurring inorganic and organic materials can influence contaminant transport and transformation in the subsurface. The geochemical conditions identified in Table 2 are often associated with unique regional conditions, specific forms of contamination, or combinations of contaminants. These conditions may present remediation challenges either on their own or when coupled with other attributes. The geochemical conditions described in Table 2 induce other related processes that either limit remedial effectiveness or induce negative secondary effects.

2.1.3.1 Extreme Geochemistry

Sites have extreme geochemistry when geochemical conditions are well outside of the range observed at typical sites. This geochemistry may limit the remedial technologies that can be applied, or may need to be a focal point of the remedial design. Under site-specific conditions, alkalinity, pH, redox conditions, salinity, ionic strength, and hardness are a few examples of the parameters that can result in extreme geochemistry.

Alkalinity is a measurement of an aquifer's overall capacity to neutralize acids. While groundwater alkalinity is usually an indicator that quantifies this capacity, the neutralization capacity of soils must also be considered because they can account for 70–90% of an aquifer's overall neutralization capacity. High or low alkalinity conditions contribute to a site's overall complexity because they reflect an aquifer's ability to withstand pH modification. For example, fermentation of organic substrate (added to promote biodegradation) at sites with elevated alkalinity can generate dissolved carbon dioxide at levels exceeding its solubility. Consequently, bubbles or vapors can be generated in the saturated zone that limit solution injectability or contribute to reductions in hydraulic conductivity.

In these same treatment applications, poorly buffered aquifers (low alkalinity) can exhibit pH decreases. Volatile fatty acids are generated from fermentation processes following carbon delivery. In a poorly buffered aquifer, these volatile fatty acids will lower the groundwater pH. Biologically mediated processes are reduced at low pH (<6), as has been widely documented for *Dehalococcoides mccartyii* in chlorinated solvent dehalogenation.

Extremes in pH generally result from acid or base releases sufficient to cause a sustained decrease or increase in soil and groundwater pH conditions. Extreme pH values or changes in redox conditions can control the dissolution of toxic minerals/metals such as arsenic, lead, and a variety of heavy metals that are naturally present in native soils. The release of naturally occurring metals due to low pH, and in some cases low oxidation-reduction potential, can result in levels of these metals that exceed drinking water criteria. These metals must then be remediated, along with the other anthropogenic contaminants.

Aquifers with high salinity or ionic strength can also be challenging. For example, when selecting reagents for injection into a high ionic strength aquifer containing fine-grained materials, the concentrations of cations such as sodium and calcium in the groundwater should be considered. Using a freshwater reagent for injection in these environments can cause dispersion and increased hydration of clay particles (Kia et al. 1987, Zhou et al. 2009), which can irreversibly clog the injection well. Instead, a reagent created to match the key cation makeup of the high salinity aquifer (brackish aquifer) should be used.

Aquifers with high salinity or ionic strength may also contain elevated competing electron acceptors beyond those observed at typical sites. Elevated sulfate concentrations, for example, are found in coastal environments and some regional geologies. These elevated concentrations of electron acceptors require large, sustained quantities of organic carbon as an electron donor to promote the highly reducing groundwater conditions needed to achieve treatment. If too little organic carbon is applied, then contaminant concentrations do not decrease because the carbon is instead wholly used by organisms to deplete the elevated concentrations of the sulfate electron acceptors.

Another added complexity of extreme geochemistry aquifers is the potential for the remedy to create an increase in hardness, total dissolved solids, iron, heavy metals, and sometimes taste and odor in the aquifer (under either engineered or natural attenuation conditions). The presence of these minerals can present remedy design challenges. For example, in soils with naturally high ferric iron composition, reduced iron minerals can contribute to extensive equipment fouling as the iron reprecipitates with either sulfide (in reduced groundwater systems) or hydroxide species (in extraction wells, injection wells, or above-grade treatment systems). This fouling can impede fluid flow to and from groundwater systems. An aesthetic criterion can also cause the water supply to be deemed nonpotable for domestic or municipal consumption. Treating the degraded groundwater for the aesthetic criterion may also be required at a cost to the community or individual well owner.

2.1.3.2 Extreme Groundwater Temperatures

Groundwater temperatures influence both the kinetic rates of chemical reactions and the activity of microorganisms performing biodegradation. For physical or chemical remedies, extreme increases in temperature are a key component to successful chemical oxidation, contribute to enhanced hydrolysis of several key chlorinated ethane contaminants that are not readily biodegradable, and are the basis of thermal remediation designs. Extreme elevated temperatures can also complicate a CSM—for example, geothermal sources may have an impact on contaminant fate and transport and can mask other fate and transport properties such as sorption and desorption. Increased temperature enhances the rate of microbial enzymatic activity and in general is correlated with an increase in growth for each incremental increase of 10ºC. This convention holds true up to approximately 37ºC, above which cell wall lysis and enzyme denaturation occur.

Conversely, low temperatures decrease the rates of chemically and biologically mediated reactions and thus may preclude using injection-based remedial technologies that rely on these reactions. Sites with cold climates (low annual or seasonal groundwater temperatures) or permafrost layers exhibit low rates of natural attenuation and thus have fewer treatment options. When coupled with other technical characteristics (such as large-scale plumes or deep groundwater contamination), sites with low temperatures can require long cleanup time frames, may have fewer effective remedial technologies available for use, and may incur increased remediation costs. While low temperatures should be considered during remedy selection, they do not entirely preclude the use of biologically enhanced remedies or natural attenuation processes, as illustrated by the use of biologically based remedies in seasonally cold climates such as the Test Area North site in Idaho. The North Pole refinery site in Alaska is another example of a site where bioremediation has been a successful remedial strategy.

2.1.4 Contaminant-Related Conditions

Contaminant-related conditions that may contribute to a site being considered complex include the presence of NAPLs, recalcitrant contaminants, high concentrations or multiple contaminants, and emerging contaminants.

2.1.4.1 NAPLs

Nonaqueous phase liquids are common but complicating contaminants. LNAPLs are less dense than water and form a separate phase in the subsurface if released in significant quantities. Examples of contaminants that form LNAPL include crude oil, gasoline, diesel fuel, and heating oil. LNAPL source zones can naturally degrade over time by processes including sorption, volatilization, and dissolution (ITRC 2009b). Large LNAPL releases, however, may migrate to the water table over a large area, leaving residual contaminant in the overlying soil that presents significant remediation challenges.

DNAPLs are denser than water and also form a separate phase in the subsurface if released in significant quantities. Examples of DNAPLs include chlorinated solvents, creosote, coal tar, chlorobenzenes, and polychlorinated biphenyls (PCBs) (USEPA 1993). Unlike LNAPL, DNAPL sinks in the subsurface below the water table and becomes sorbed into low-permeability zones or bedrock fractures. With time, DNAPL can then back-diffuse into more permeable zones and cause persistent groundwater plumes. Low-permeability zones are hard to treat with standard technologies and can act as a contaminant source to more permeable zones for decades or even centuries (ITRC 2011b). DNAPL transport varies with contaminant viscosity, solubility, and other properties. For example, chlorinated solvents behave differently than coal tar. The presence of DNAPL often makes in situ remediation more difficult and expensive (McCarty 2010, Stroo et al. 2012, Suchomel et al. 2014).

A range of technical challenges faced at DNAPL sites were described in the ITRC *Integrated DNAPL Site Strategy* (IDSS) guidance (ITRC 2011b) and by the NRC (2013). The overarching technical challenge is that many complex sites have a heterogeneous distribution of contaminant mass, leading to substantial back-diffusion from bedrock/soils to remediated groundwater. This condition, combined with the presence of high-concentration source areas at many sites, makes characterization and remediation difficult and leads to persistent and often large contaminant plumes in groundwater (USEPA 2004e).

2.1.4.2 Recalcitrant Contaminants

Recalcitrant contaminants do not easily degrade and may exhibit other characteristics (such as radioactivity, phase change, molecular states, or molecular bonding) that resist remediation within a reasonable time frame. Examples of these chemicals include polyaromatic hydrocarbons (PAHs), PCBs, poly- and perfluoroalkyl substances (PFAS), several organochlorine pesticides, dioxins, furans, metals, and radionuclides. Brominated flame retardants are another newly identified class of chemicals in this category. The presence of bioaccumulative and endocrine disruptor compounds in the aquatic environment, food chain, and human population can also add significantly to site complexity. Sometimes treating these compounds may result in a byproduct that must also be managed as a waste (such as radionuclides) and may pose special management and disposal issues (USEPA 2004b, 2007b, Prakash et al. 2013). Treatment may also produce intermediate products of unknown toxicity.

2.1.4.3 High Concentrations or Multiple Contaminants

In some cases, multiple contaminants create uniquely complex treatment difficulties. A treatment appropriate for one contaminant may not treat the entire mix or may even interfere with the remediation of another contaminant. Mixtures such as chlorinated solvents and 1,4-dioxane or a combination of metals and volatile organic compounds can be difficult to remediate because the chemical and physical properties differ, which creates different plume characteristics and requires different treatment technologies. For example, chlorinated solvents can be anaerobically bioremediated, but 1,4-dioxane generally requires advanced oxidation processes.

High concentrations of contaminants may result in the site becoming anaerobic or may overwhelm the natural attenuation capacity of the system. In other situations, the inherently difficult nature of even a single contaminant—such as a radionuclide that is resistant to removal, located in an inaccessible area, and persistent by nature—leads to complexity. This complexity limits treatment options, and, eventually, increases the time required for removing the contamination.

2.1.4.4 Emerging Contaminants

Some of the emerging contaminants, such as PFAS or 1,4-dioxane, have only limited remedial technologies, making it difficult to reach site objectives. PFAS have been used for decades in products that resist heat, oil, stains, grease, and water and because PFAS were designed to be chemically and thermally stable, they are extremely resistant to breakdown in the environment. ITRC is currently developing guidance for addressing PFAS (ITRC 2017b). Often, as is the case with PFAS and 1,4-dioxane, these contaminants are soluble in water and are relatively resistant to biodegradation (USEPA 2014a). Some of these emerging contaminants (such as PFOS and PFOA) are also detected in water supply systems. Widespread groundwater effects, especially in water supply systems, may result in focused treatments at wellheads in the short term with much longer time frames required to meet all site objectives.

2.1.5 Large-Scale Sites

Although size alone does not make a site complex, contaminated sites often cover many square miles. Characteristics of large-scale sites contribute to several complications that even under the best of circumstances lead to longer time frames for characterization and remediation. Examples of characteristics that may result in a site being considered complex include location, nature and extent of contamination; depth of contamination; number, type and proximity of receptors; and comingled plumes. The complications and costs that accompany larger scale sites impose limitations on what can be accomplished within a given (presumably reasonable) time frame. The difficulties of responding to logistical challenges, workforce and workload management, responding to uncertainties, and technical difficulties increase with increasing scale of the area to be addressed and the number of potential sources identified. Case studies of large-scale sites are summarized below. Previous publications (such as NRC 2013) have also highlighted case studies of remediation complexities at large-scale sites.

Hanford Site 200-ZP-1 Operable Unit Case Study: Complexities and Cleanup Path

DOE’s Hanford Site, located in southeastern Washington State, was formerly used to produce plutonium for national defense under the Manhattan Project. This process used nuclear reactors to irradiate fuel elements, followed by chemical processing to separate isotopes of interest. During these processes, waste containing solvents, multiple organic compounds, a range of radionuclides, and inorganic compounds was disposed to the subsurface. The extent of groundwater contamination exceeds more than 12 square kilometers and includes comingled plumes of carbon tetrachloride, chloroform, TCE, nitrate, chromium, tritium, uranium, and technetium. Groundwater contamination extends to depths of about 250 feet. Waste inventory records show that carbon tetrachloride discharges alone range from 600,000 kg to 1,000,000 kg. Approaches to cleanup include source removal from the vadose zone and 30 years of active groundwater pump-and-treat. The treatment train consists of ion exchange, soil vapor extraction and vapor-phase granular activated carbon (SVE/GAC), and ex situ bioremediation, along with in situ monitored natural attenuation to achieve drinking water standards in approximately 130 years. More details are provided in the full case study.

2.1.5.1 Location, Nature, and Extent of Contamination

Many confounding factors may influence the size and distribution of a plume. Over decades, the practices resulting in a release may have been altered, stopped, or even shifted from location to location. Property downgradient from source area(s) that were originally undeveloped and open might now be developed, resulting in potential vapor intrusion (VI) concerns and lower groundwater cleanup objectives. In some cases, contamination may be present beneath densely populated areas (such as a large downtown). When an industrial facility occupies many square miles with many close or separated potential sources, the scale of both areal extent, number of activities to investigate, and the variety of sources and contaminants contribute to the complexity of the site. Among the challenges associated with a large and complex groundwater plume is the increasing chance that significant downward migration into productive high-yielding aquifer zones and entry into municipal supply well fields has already occurred. Alternatively, the plume may expand into brackish (>1,000 ppm total dissolved solids), nonpotable water that should not be pulled into the cone of depression from a remedial system.

2.1.5.2 Depth of Contamination

Some sites, particularly in the western United States, are characterized by deep groundwater. Depths to groundwater greater than 250 feet exist at several well-documented complex sites. For example, depth to groundwater at the Hanford site in Washington State can reach approximately 350 feet (Looney 2012) and depth to water at the Pantex Plant in Texas is approximately 280 feet. Vadose zone characterization, monitoring and remediation at these depths is challenging because of limitations in instrumentation and monitoring technology, difficulties in drilling to greater depths, and challenges with injecting nutrients/reagents at depth. At the North Pole Refinery, Alaska, off-site contamination has been detected in the subpermafrost in private wells as deep as 320 feet (Alaska Department of Environmental Conservation 2015).

Case Study: Test Area North

The Test Area North site at DOE's Idaho National Laboratory includes a two-mile trichloroethylene (TCE) plume with source area concentrations of over 20,000 µg/L. TCE is present at depths up to 200 to 300 feet. A ROD amendment signed in September 2001 documents regulatory approval of enhanced in situ bioremediation (ISB) as the final remedy for the plume hot spot and MNA as the final remedy for the distal portion of the plume. ISB has been implemented at the site since 1999. Both lactate and whey have been injected as electron donor biostimulants to promote microbial activity. Microbial community evaluation showed shifts in the microbial population in response to the electron donor injection. Complete dechlorination of TCE to ethene was observed in several monitoring wells at the site. MNA is predicted to achieve MCLs by 2095. More details are provided in the full case study.

2.1.5.3 Number, Type, and Proximity of Receptors

Plumes may be within or near drinking water aquifers or other receptors such as endangered species habitat, wetlands, or other environmentally sensitive areas. The likelihood for resource degradation may increase the difficulty of remediation. Protecting human health and the environment is paramount in these situations, often requiring interim and temporary systems while the project proceeds towards a more permanent solution. The presence of contamination in an aquatic environment introduces additional potential human and ecological receptors. Multiple ecological and human receptors also complicate a site.

2.1.5.4 Extensive or Comingled Plumes

Large plumes may also have acquired additional contributing sources, both industrial and nonindustrial, through leaky sewers, agriculture, and landscaping practices. These contributing sources add to legal and risk management complications as well as remediation challenges. From a remediation perspective, comingled sources in a large plume make it difficult to find and remediate the sources and to know if all the sources have been identified. For naturally occurring compounds such as metals, natural variability in the environment may make it difficult to establish background conditions. Where plumes are viewed as regional or multisource, assigning liability and recouping expenditures becomes a challenge. Additionally, the options for remediation may be even more limited because the available financial resources are spent more for wellhead treatment than for identifying sources.

Case Study: Rocky Flats

The Solar Ponds Plume at Rocky Flats is a mixed uranium and nitrate/nitrite plume, with a smaller colocated organic compound plume. Because these contaminants are now present as secondary sources within a low-permeability matrix, it will be many decades before the plume meets standards. Because the plume is comingled, it requires phased treatment. More details on this site are provided in the full case study.

2.2 Nontechnical Challenges

Although nontechnical challenges exist at every site, it is often the combination of nontechnical and technical challenges that results in a complex site. Generally, the more technically challenging a site is, the longer it will take to achieve site objectives. Often because of the technical challenges and longer remediation duration, nontechnical challenges become more evident. Recognizing these relationships and identifying the nontechnical challenges early in the process helps to establish site objectives that can be achieved within a reasonable time frame. Table 3 summarizes some of the nontechnical challenges faced at complex sites. Additional information is provided in this guidance on setting and tracking ICs and the long-term management of complex sites.

Table 3. Nontechnical challenges for complex sites

Nontechnical Challenges	Examples
Site objectives	• Societal expectations and social acceptability • Changing site objectives • Adopting site objectives that differ from promulgated screening levels or closure criteria (such as MCLs)
Managing changes that may occur over long time frames	• Phased remediation • Future use • Site management • Multiple responsible parties • Staff turnover/Loss of institutional knowledge • Litigation
Overlapping regulatory responsibilities	• Federal and state cooperation • Changing laws and regulation • Financial responsibility • Orphan sites • Contaminants without regulatory criteria or guidance (such as emerging contaminants)
ICs	• Tracking and managing ICs • IC enforcement • Long-term management of institutional controls
Changes in land use	• Changing land use or water use • Multiple owners • Site access
Funding	• Lack of funding (state, federal, or private industry) • Politics that alter funding/program priorities • Unwilling or unknown RPs

Similar nontechnical challenges have been identified by other agencies (such as International Atomic Energy Agency 2002). In addition to the nontechnical challenges listed, accounting for stakeholder perspectives is a significant challenge at some sites.

2.2.1 Site Objectives

A typical site objective is to restore groundwater to beneficial use. In some cases, this site objective cannot be technically achieved in a reasonable time frame, even though the objective was adopted in accordance with regulatory requirements that reflect societal expectations (ITRC 2011b). For sites where complete restoration/reuse is not the objective, alternative site objectives may be established based on site-specific conditions, such as classification of the underlying aquifer as a nondrinking water area (see, for example, ITRC team survey results from state regulators in Appendix A). If an alternative objective is to be

Changing Site Objectives

The site objective at a hypothetical site may be to restore the groundwater to beneficial use at some point in the future. In this case, a less aggressive remedy might be chosen based on the assumption of enough time (50 or more years) to achieve the site objective, because there was no foreseeable use of the resource. Drinking water standards are appropriate because the regulatory authority has classified the aquifer as a potential drinking water source. Five years into the remediation, it may be determined that the resource will be established, however, it must be acceptable to the regulatory agencies and stakeholders. This guidance provides more detail on technical and nontechnical aspects of setting and revisiting site objectives, including management approaches that are allowable under certain regulatory programs for specific circumstances. Beyond site objectives, there may be additional societal expectations and social acceptability criteria for remediation projects. For example, land reuse while remediation is occurring may be important to stakeholders. The use of GSR practices may be important to some stakeholders. Social acceptability can also inform the selection of remedial technologies and associated interim objectives.

needed more quickly because of unprecedented and unexpected local development. The site objective of restoration now must be achieved within 15 years as compared with 50 or more years on which the remedy was based. Therefore, the site objective should be modified and potentially a different remedy chosen to meet that new objective.

2.2.2 Managing Changes that May Occur Over Long Time Frames

The long time frame for remediation adds to complexity because continuity must be maintained throughout remediation. Many complex sites may require different remedies (ex situ, in situ) that must be implemented in phases (ITRC 2011b). Each phase could last several years, during which time there may be regulatory changes that affect oversight (such as going from a process of approval at every step to a privatized program with minimal oversight). Other regulatory changes could include changes in cleanup requirements (for example MCLs or state groundwater standards), changes in risk assessment approaches, or changes in which agency has authority over the project. As with any long-term project, there is also the likelihood of changes in personnel and the loss of institutional knowledge. Changes in land use/redevelopment may change human health and ecological risk assessment scenarios. Water use may change along with land use; groundwater and surface water that was once used for irrigation or agricultural purposes may be converted to city water supplies. These changes can be monitored and mitigated using a project risk register.

2.2.3 Overlapping Regulatory Responsibilities

At some large complex sites, numerous regulatory agencies may become involved over the long time frames that these sites require. There may not be clear cut relationships between these agencies and each agency may follow different policies and practices in relation to these contaminated sites. One agency may be responsible for overseeing remediation and another may be responsible for long-term management or redevelopment. The remediation oversight agency may realize that it may be a very long time before redevelopment can occur, and the redevelopment agency may push for faster (and perhaps less thorough) remediation so that land can be reused faster. These conflicting goals can present nontechnical challenges to remediation management. On another level, decisions made by state and federal agencies may have long term effects on local authorities and programs. In addition, those local authorities may have responsibility for local planning, record keeping, and day-to-day oversight that have significant implications for the long-term management of contaminated sites.

Overlapping Regulatory Responsibilities

An 850-acre Massachusetts Superfund site has multiple uses and multiple owners and, for the most part, does not appear to be contaminated. The primary issue is contaminated groundwater that affected two municipal wells. A portion of the site is owned by the municipality, which decided to erect a solar array on its property. The municipality applied to the state regional environmental regulatory office for permits (for wetlands issues) and was required to go to another state environmental agency for endangered species issues. Even though the property was located within the Superfund site, the state environmental agency overseeing the site cleanup was never informed of the project until after it was built.

Sites can also transition from one regulatory program to another. For example, a site may start out under a state program and transition to a federal Superfund site. During the transitional period, some work may continue under the state program while other activities are directed by USEPA. Different programs may have different requirements (such as presumptive approval by the state agency versus a written letter of approval by USEPA). This situation can create confusion for the responsible parties and others conducting the work regarding what is required by each program, and the potential need to repeat or expand work due to different agency requirements. State and federal laws and regulations governing cleanups of contaminated sites can also change with time and administrations. Risk factors and standards can change, potentially requiring different remedial approaches.

At many large sites, the state and USEPA both have concurrent regulatory roles. Multiparty agreements at these sites serve to essentially combine the regulatory authorities and to determine which agency has a lead regulatory role in certain areas and projects. At some sites, such as Hanford and Rocky Flats, the division is generally geographic with an overlay of regulatory authority.

2.2.4 ICs

Use restrictions placed on sites in the form of ICs can add complexities as well. Once the ICs are established, a mechanism must be created to track and manage them. If the conditions of the IC are violated (for example a private drinking water well is drilled in an area where groundwater use for consumption is prohibited), an authority must exist that can address the violation and prevent anyone from drinking the contaminated water (ITRC 2016b). Often ICs are created in the form of deed restrictions; it may be up to a potential new owner to use due diligence to discover that a deed restriction exists. Once an IC is no longer necessary, a clearly defined process should describe how to remove the IC and what parties are responsible for removing it.

2.2.5 Changes in Land Use

Over the long term, land use changes are typically a result of changes in property ownership. Ownership, use, and zoning of adjacent lands may change over time, particularly for large-scale or regional sites. Off-site redevelopment may affect site objectives by introducing potential receptors or exposure pathways. For example, off-site zoning may change from industrial to residential, affecting site remediation goals. Vapor intrusion may be identified as a potential pathway if off-site redevelopment occurs. If possible, local land use agencies can be contacted and given an opportunity to comment on site remediation plans. These agencies may know of potential future development or have local master plans that call for redevelopment of properties near the site.

Any change in site ownership or the ownership of a portion of the site should be coordinated with the site remediation. Information to convey to the new owner includes property restrictions (such as groundwater use restrictions), access agreements, and active remediation components that may exist on different parcels (such as groundwater extraction wells). Restricting access to areas which may be covered by buildings that are part of an active facility may affect investigating, characterizing, or remediating portions of a property. Different regulatory agencies become involved with site redevelopment. Having a reliable means to track and communicate the state of remediation between agencies, owners, and prospective purchasers of affected properties is important to the long-term integrity of the remedy and ongoing protection to human health and the environment. Fortunately, many states, as well as independent organizations, have developed guidance to assist those who are responsible for long-term stewardship of affected lands (ITRC 2016b).

2.2.6 Funding

Complex sites by their nature often require significant financial resources. Long-term site management funding for complex sites can be a challenge, not only for the private sector responsible party, but for state and federal programs as well. In the private sector, setting aside funds for future environmental work affects profitability and investments in capital projects. On the other hand, cleaning up a site sooner adds to its value (International Atomic Energy Agency 2002). For governmental agencies, there are many competing needs for limited available funding and adequate financing to fully address orphan or fund-led sites may not be available. This situation is concerning because inadequate funding can lead to underdeveloped CSMs that do not account for key technical complexities, thus resulting in unrealistic site objectives, ineffective remedies, and overuse of ICs.

Splitting Costs at Superfund Sites

In the federal Superfund program, states become responsible for long-term operation and maintenance (O&M) of remedies that may require decades to reach site objectives. If an entirely different remedy becomes necessary, states could find themselves paying 100% of a potential multimillion dollar remedy. The normal split for a remedy at a Superfund site is USEPA 90% and state 10% for the first ten years, with the state paying 100% of the costs after that.

2.3 Developing a CSM Based on Site Characteristics

A thorough CSM describes the processes at a site that control the transport of contaminants from sources through environmental media to environmental receptors. It is a valuable tool for planning, data interpretation, and for communicating with the public. A CSM can also help identify where additional information is needed. Developing a CSM is a crucial step in setting both site objectives and interim objectives. Several reference documents provide detail on CSMs and their importance in understanding and remediating sites (USEPA 2011a, ASTM 2008, ITRC 2011b, USACE 2012). For complex sites, CSMs typically describe the technical characteristics but may not present context for nontechnical challenges. The focus on technical characteristics in a CSM could be balanced by considering nontechnical challenges and accounting for these in site decision documents, such as National Environmental Policy Act (NEPA)/California Environmental Quality Act (CEQA) reports.

USEPA (2011a) has summarized the development of a CSM throughout a project. In practice, the CSM should be treated as a dynamic tool to be updated throughout the stages of a project lifecycle. The flowchart in Figure 1 identifies when it is necessary to update the CSM within the adaptive site management process. In addition, it is a good practice to update the CSM whenever additional relevant data are acquired.

"Six Stages of CSM Maturity" (USEPA 2011a)

"Key Points in the Development of a CSM

*1) **Preliminary CSM Stage** – Project milestone or deliverable based on existing data; developed prior to systematic planning to provide fundamental basis for planning effort.*

*2) **Baseline CSM Stage** – Project milestone or deliverable used to document stakeholder consensus/divergence, identify data gaps, uncertainties, and needs; an outcome of systematic planning.*

Key Points in the Evolution and Refinement of a CSM

*3) **Characterization CSM Stage** – Iterative improvement of CSM as new data become available during investigation efforts; supports technology selection and remedy decision making.*

*4) **Design CSM Stage** – Iterative improvement of CSM during design of the remedy; supports development of remedy design basis and technical detail.*

*5) **Remediation/Mitigation CSM Stage** – Iterative improvement of CSM during remedy implementation; supports remedy implementation and optimization efforts, provides documentation for attainment of cleanup objectives.*

***Post Remedy CSM Stage –** Comprehensive site physical, chemical, geologic, and hydrogeologic information of CSM supports reuse planning; documents institutional controls and waste left on site; and other key site attributes."*

The goal of this process is to develop a CSM with sufficient depth and clarity to accurately assess risks and develop appropriate remediation strategies. To accomplish this goal, the CSM aligns contaminant distribution data with site geologic heterogeneity and groundwater flow conditions at a spatial resolution appropriate to the site-specific site objectives. The CSM includes all contaminated media, multiple types of contaminated media may increase the site complexity.