United States Environmental Protection Agency

Office of Land and Emergency Management
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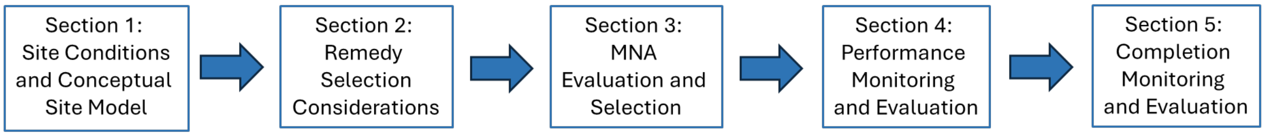
Recommended Summary Checklist for a Superfund Monitored Natural Attenuation Evaluation for Groundwater

Purpose and Use

This *Recommended Summary Checklist for a Superfund Monitored Natural Attenuation Evaluation for Groundwater* ("MNA Checklist") identifies criteria to assist in the potential selection and subsequent performance evaluation of a monitored natural attenuation (MNA) remedy for groundwater at Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) National Priorities List sites and Superfund Alternative (SA) approach sites. **MNA in groundwater may be suitable for a broad spectrum of contaminant classes, including organics, inorganics, and radionuclides**. The MNA Checklist does not create or alter any existing regulations.

The checklist helps guide and promote the appropriate collection of data and use of the MNA evaluation process to encompass key technical and policy components of the 1999 *Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank Sites* (EPA 1999) and the 2015 *Use of Monitored Natural Attenuation for Inorganic Contaminants in Groundwater at Superfund Sites* (EPA 2015) guidance documents and other Superfund remedy documents. The checklist is a tool to help those in the regulated and regulatory communities that collect and review information to make an MNA decision, as well as identify major processes that should be carried out for performance monitoring and successful implementation of MNA, as shown in Figure 1. Awareness of these steps during evaluation of MNA as a potential alternative will increase likelihood of successful remediation through MNA or other methods.

Figure 1: MNA Conceptual Process



As mentioned in the 1998 *Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Ground Water* (EPA 1998), MNA is generally evaluated in a feasibility study or a focused feasibility study as a remedial alternative to achieve groundwater restoration. Typically, MNA is used in conjunction with active remedial measures. "Several remedial approaches could be appropriate to address the dissolved plume, one of which could be MNA under suitable conditions. However, the evaluation of natural attenuation processes and the decision to rely on MNA for the dissolved plume should be distinct from the recognition that restoration of a portion of the plume is technically impracticable (i.e., MNA should **not** be viewed as a direct or presumptive outcome of a technical impracticability determination.)" (emphasis in original) (EPA 1999). For example, active remedial measures could be applied in areas with high concentrations of contaminants, whereas MNA could be used for low concentration areas of the distal or downgradient portion of the groundwater plume or as a follow-up to active remedial measures. MNA may be considered as the sole remedial action or as a final polishing step in a phased remedial approach, usually after source reduction and/or control actions have been completed under both scenarios. **Use of MNA as a sole remedial action or as part of a phased remedial approach should be supported by lines of evidence justifying its appropriateness.**

MNA should not be presumed as a viable remedial alternative without supporting lines of evidence. The current and future groundwater valuation and use at a site should be a component of the remedial decision when evaluating MNA. For example, identifying receptor demographics (human health and ecological) for current and future groundwater demand is an essential criterion for determining the groundwater classification at the site, which will help with determining an appropriate groundwater remedial timeframe and the potential application of MNA.

Practitioners engaged in preparing and reviewing MNA evaluations should use the MNA Checklist to identify whether these supporting lines of evidence exist, as well as to promote technical adequacy and consistency. Use of the MNA Checklist can support the consideration of each topic in the appropriate context and sequence. However, because the MNA evaluation process is site specific, and because all items in the checklist are not applicable to every site, other additional technical criteria, including technical criteria not addressed in this checklist, may also be included when considering MNA as a remedial alternative. The checklist should be considered in totality when evaluating the (1) appropriateness of selecting MNA, (2) performance of the remedy, and (3) effectiveness of the remedy. In general, the MNA evaluation should address each of these topics and any selection components included in appropriate documents in the administrative record. **A missing checked box should not automatically rule out the possibility of selecting MNA as a viable remedial alternative.**

Implementation

The term "monitored natural attenuation," as used in this checklist, refers to the reliance on natural attenuation processes (**within the context of a carefully controlled and monitored site cleanup approach**) to achieve site-specific remedial objectives within a reasonable timeframe compared with that offered by other more active methods. Prior to selection of the remedy, the reasonable range of alternatives, including any MNA alternatives, undergo the nine-criteria evaluation provided in 40 CFR 300.430(e)(9)(iii). This evaluation helps inform the remedy selection process by comparing the reasonable range of alternatives with each other. The "natural attenuation processes" that are at work in an MNA remedial approach may include a variety of physical, chemical, and/or biological processes that, under favorable conditions, act without human intervention to reduce the mass, toxicity, mobility, volume, and/or concentration of contaminants in soil or groundwater.

These in situ processes include biodegradation; dispersion; dilution; sorption; volatilization; radioactive decay; and chemical or biological stabilization, transformation, or destruction of contaminants. When evaluating natural attenuation processes for site remediation, the U.S. Environmental Protection Agency (EPA) prefers processes that degrade or destroy contaminants (EPA 1999). Additionally, the EPA expects that MNA would generally be most appropriate for sites where the contaminant plumes are no longer increasing in extent or are shrinking (EPA 1999, p. 18).

Natural attenuation processes typically occur at all sites but to varying degrees of effectiveness depending on the types and concentrations of contaminants present and the physical, chemical, and biological characteristics of the soil and groundwater. Even though these mechanisms are present, they may not be sufficient to meet the goals of the Superfund remedial program for groundwater restoration in a reasonable timeframe.

While MNA is often considered “passive” remediation because natural attenuation processes occur without human intervention, its use at a site does not preclude the use of “active” remediation or the application of enhancers of biological activity (e.g., electron acceptors, nutrients, and electron donors), chemical activity (e.g., in situ chemical oxidation [ISCO], in situ chemical reduction [ISCR]), or physical activity (e.g., solidification). **However, a remedy that includes the introduction of an enhancer of any type is no longer considered to be “natural” attenuation while the enhancer is still active or present**. Use of MNA does not imply that activities (and costs) associated with investigating the site or selecting the remedy (e.g., site characterization, risk assessment, comparison of remedial alternatives, performance monitoring, contingency measures) have been eliminated. These elements of the investigation and cleanup must still be addressed as required under the Superfund remedial program, regardless of the remedial approach selected. In some cases, throughout the entirety of the CERCLA process and subsequent operations and maintenance, the cost to characterize the site and implement the remedy may be greater for MNA than with active remedies.

Section 1: Site Conditions and Conceptual Site Model

Associated section of the MNA Checklist: Section 1. Site Conditions and Conceptual Site Model

Decisions to employ MNA as a remedy or remedy component should be thoroughly and adequately supported with site-specific characterization data and analysis. In general, the level of site characterization necessary to support a comprehensive evaluation of MNA may be more detailed than that needed to support active remediation (EPA 1999). Site characterization for natural attenuation generally warrants a quantitative understanding of source mass (e.g., distribution, nature); groundwater flow (including preferential pathways); contaminant phase distribution throughout the plume and partitioning between soil, groundwater, soil gas, and non-aqueous phase liquids (NAPLs); rates of biological and nonbiological (i.e., chemical) transformation; and an understanding of how these factors are likely to vary with time (EPA 1999). The EPA recommends this information be evaluated because contaminant behavior is governed by dynamic processes that must be well understood before MNA can be selected or appropriately applied at a site. Demonstrating the efficacy of MNA may benefit from analytical or numerical simulations of complex attenuation processes. Such analyses are useful to demonstrate natural attenuation's ability to meet remedial objectives and typically require a detailed conceptual site model (CSM) as a foundation. The CSM should be updated throughout the MNA remedy because of changes in site conditions and/or the emergence of new information.

The EPA recommends the use of CSMs to integrate data and guide both investigative and remedial actions. However, practitioners should collect sufficient field data to test conceptual hypotheses and exercise caution not to “force fit” site data into a preconceived, and possibly inaccurate, conceptual representation. In some cases, site characterization may require a higher level of site-specific data. Site characterization should include collecting data to define (in three spatial dimensions over time) the nature and distribution of contaminants of potential concern and contaminant sources **as well as potential impacts on receptors**.

Source Control

Evaluation of a source and its impact on groundwater is essential to the CSM and influences what source control measures should be evaluated as part of the remedy decision process at all groundwater sites, particularly where MNA is under consideration. CERCLA and the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) generally provide for the use of source control actions where practicable, and the EPA expects that source control measures will be taken at most sites (EPA 1999). Source control measures include removal, treatment, or containment, or a combination of these approaches. The EPA prefers remedial options that remove NAPLs and treat source materials, especially those that constitute “principal threat wastes” (EPA 1999). Principal threat wastes are those source materials considered to be highly toxic or highly mobile that generally cannot be reliably contained or would present a significant risk to human health or the environment should exposure occur. They include liquids and other highly mobile materials (e.g., solvents) or materials having high concentrations of toxic compounds (EPA 1991).

Source control may offer greater confidence in MNA success and may reduce MNA timeframes because of the termination/reduction of contaminant fluxing from the source/NAPL to the groundwater. Control of source materials is a highly effective means of ensuring the timely attainment of remedial objectives and should be evaluated and implemented as appropriate where source material remains at the site. The EPA also encourages the consideration of innovative technologies for source control or “active” components of the remedy, which may offer greater confidence and reduced remedial timeframes at modest additional cost. Following source control measures, natural attenuation may effectively achieve remedial objectives at some sites without the aid of other (active) remedial measures (EPA 1999). Where conditions are favorable, natural attenuation processes may reduce contaminant mass or concentration at sufficiently rapid rates to be integrated into a site’s soil or groundwater remedy.

Section 2: Remedy Selection Considerations

Associated section of the MNA Checklist: Section 2. Remedy Selection Considerations

MNA should not be considered a default or presumptive remedy at any contaminated site and should always be supported by lines of evidence justifying the effectiveness of this approach.

Sites Where Monitored Natural Attenuation May Be Appropriate

MNA is appropriate as a remedial approach when it can be demonstrated as capable of achieving a site's remediation objectives within a timeframe that is reasonable compared with those offered by other methods and where it meets the applicable remedy selection criteria (if any) for the particular Office of Land and Emergency Management (OLEM) program (EPA 1999; EPA 1990, p. 8733–8734). The EPA expects that MNA will be most appropriate when used in conjunction with other remedial measures (e.g., source control, groundwater extraction) or as a follow-up to active remedial measures that have already been implemented.

The most important considerations regarding the suitability of MNA as a remedy include whether the contaminants are likely to be effectively remediated by natural attenuation processes, the stability of the groundwater contaminant plume and its potential for migration, and the potential for unacceptable risks to human health or environmental resources by the contamination (EPA 1999, p. 17–18). MNA should not be used where it could result in plume migration or unacceptable adverse impacts to human health and environmental resources. The most appropriate candidate sites for MNA remedies are sites where the contaminant plumes are shrinking or no longer increasing in extent and where MNA satisfies the nine evaluation criteria in 40 CFR 300.430(e)(9)(iii).

It is important to consider the aquifer classification when making an MNA decision. MNA is generally less appropriate for a Class I (high-value) aquifer. MNA may also be less appropriate for a Class IIA aquifer that may need an active remedy with a faster remedial timeframe because it is needed as a current or potential source of drinking water. An evaluation of the suitability of MNA will be largely based on the groundwater use and demographics at a site. MNA may be more appropriate for a Class IIB aquifer that is not currently being used as a drinking water source and for which the slightly longer remedial timeframe usually attributed to MNA (in relation to an active remedy) would be considered reasonable (EPA 1990, p. 8732–8735).

Reasonable Timeframe for Remediation

The EPA recognizes that determination of a "reasonable" timeframe for attaining remedial objectives is a site-specific determination. The NCP preamble suggests that a "reasonable" timeframe for a remedy relying on natural attenuation is generally a "...timeframe **comparable** to that which could be achieved through active restoration" (EPA 1990, p. 8734 emphasis added). The NCP preamble further states that "[t]he most appropriate timeframe must, however, be determined through an analysis of alternatives" (EPA 1990, p. 8732). To ensure that these estimates are comparable, assumptions should be consistently applied for each alternative considered. Thus, determination of the most appropriate timeframe is achieved through a comparison of estimates for all appropriate remedy alternatives (EPA 1999).

The EPA recommends comparing the approximate timeframes needed to attain groundwater cleanup levels for both active and passive (i.e., MNA) alternatives. This comparison will inform remedy selection for the remedial objective of restoring groundwaters to beneficial use.

The timeframe required for MNA remedies is often longer than that required for more active remedies. Adequate performance monitoring and contingency remedies for MNA remedies (both discussed in later sections of this document) should be used. When determining reasonable timeframes, the uncertainty in estimated timeframes should be considered, as should the ability to establish performance monitoring programs that can verify the expected performance of natural attenuation in a timely manner (e.g., as would be required in a Superfund five-year remedy review). Computer models, such as MODFLOW and REMChlor, can be used to *estimate* timeframes; however, care must be taken to interpret the outputs generated. When MNA is used as a polishing step, timeframes should be recalculated as the remedial action progresses because aquifer conditions may change following implementation of an active remedy.

The EPA and other regulatory authorities should consider several factors (e.g., beneficial use designation, comparison with active remedy timeframes) when evaluating reasonable timeframes for MNA at a given site. These factors, overall, should allow the overseeing regulatory authority to determine whether a natural attenuation remedy (including institutional controls [ICs], where applicable) will be fully protective of human health and the environment, and whether the site remedial objectives and the time needed to meet them are consistent with the regulatory expectation that contaminated groundwaters will be restored to beneficial uses within a reasonable timeframe. **When these conditions are not expected to be met using MNA, a remedial alternative expected to meet these expectations should be selected.**

Section 3: MNA Evaluation and Selection

Associated section of the MNA Checklist: Section 3. MNA Evaluation and Selection

Once site characterization data have been collected and a comprehensive CSM developed, the next step is to evaluate the potential efficacy of MNA as a remedial alternative.

Lines of Evidence for MNA Selection

Evaluating the efficacy of MNA involves collecting site-specific data that is sufficient to estimate with an acceptable level of confidence both the rate of attenuation processes and the anticipated time required to achieve remedial objectives. A three-tiered approach to conducting such an evaluation is becoming more widely practiced and accepted (EPA 1999). In this approach, successively more detailed information is collected as necessary to provide a specified level of confidence for the estimates of attenuation rates and remedial timeframe. These three tiers of site-specific information, or “lines of evidence,” are:

1. Historical groundwater and/or soil chemistry data that demonstrate a clear and meaningful trend (for guidance on statistical analysis of environmental data, please see EPA 1989, 1992, 1993, and Gilbert 1987) of decreasing contaminant mass and/or concentration over time at appropriate monitoring or sampling points. In the case of a groundwater plume, decreasing contaminant concentrations should not be solely the result of plume migration. The primary attenuating mechanism should also be understood for all classes of contaminants (i.e., inorganic, organic, and radionuclide).
2. Hydrogeologic, geochemical, and biological data that can be used to demonstrate indirectly the type(s) of natural attenuation processes active at the site and the rate at which such processes will reduce contaminant concentrations to required levels. For example, characterization data may be used to quantify the rates of contaminant sorption, dilution, or volatilization, or to demonstrate and quantify the rates of biological degradation processes occurring at the site.
3. Data from field or microcosm studies (conducted with actual contaminated site media) that directly demonstrate the occurrence of a particular natural attenuation process at the site and its ability to degrade the contaminants of concern (typically used to demonstrate biological degradation processes only).

Unless the EPA or the overseeing regulatory authority determines that historical data (number 1 above) are of sufficient quality and duration to support a decision to use MNA, data characterizing the nature and rates of natural attenuation processes at the site (number 2 above) should be provided. When the latter are also inadequate or inconclusive, data from microcosm studies (number 3 above) may also be necessary.

In general, more supporting information may be required to demonstrate the efficacy of MNA at sites with contaminants (1) that do not readily degrade through biological processes (e.g., most non-petroleum organic compounds, inorganics), (2) that transform into more toxic and/or mobile forms than the parent contaminant, or (3) where monitoring has been performed for a relatively short period. The amount and type of information needed for such a demonstration will depend on several site-specific factors, such as the nature and extent of the contamination, the proximity of receptors and the potential risk to those receptors, and other characteristics, such as hydrogeology, climatic conditions, and biota.

Parties responsible for site characterization and remediation should ensure that capable technical specialists with expertise in the relevant sciences collect and evaluate all data and analyses needed to demonstrate the efficacy of MNA. Furthermore, the EPA expects that documenting the level of confidence on attenuation rates will provide more technically defensible predictions of remedial timeframes and form the basis for more effective performance monitoring programs (EPA 1999).

It is important to note that this concept:

- Applies to dissolved-phase contaminants on leaving the source.
- Accounts for all attenuation mechanisms occurring throughout the plume.
- Is NOT used to estimate contaminant plume time to reach remedial goals.

Contaminants of Concern

It is common practice when conducting remedial actions to focus on the most obvious contaminants of concern, but other contaminants may also be of significant concern in the context of MNA remedies. In general, since engineering controls are not used to control plume migration in an MNA remedy, decision makers need to ensure that MNA is appropriate to address all contaminants that represent an actual or potential threat (e.g., TCE to vinyl chloride, cesium-137 to barium-137m) to human health or the environment. Some natural attenuation processes may result in the creation of transformation products that are more toxic and/or mobile than the parent contaminant (e.g., degradation of TCE to vinyl chloride) (EPA 1999).

See pages 3–4 of *Use of Monitored Natural Attenuation for Inorganic Contaminants in Groundwater at Superfund Sites* (EPA 2015) for additional information regarding inorganics and radionuclides.

Section 4: Performance Monitoring and Evaluation

Associated section of the MNA Checklist: Section 4. Performance Monitoring and Evaluation

Performance monitoring is a critical element of all response actions to evaluate remedy effectiveness and ensure protection of human health and the environment. “Performance monitoring is of even greater importance for MNA than for other types of remedies due to the potentially longer remediation timeframes, potential for ongoing contaminant migration, and other uncertainties associated with using MNA” (EPA 1999). Additional considerations for performance monitoring should include the effect of seasonal variability (i.e., annual precipitation, spatial patterns of recharge, frequency, magnitude, and duration of severe storms, droughts, significant changes to range and variability in atmospheric temperatures, change in nearby surface water levels).

Details of the monitoring program should be provided to the EPA or the overseeing regulatory authority as part of any proposed MNA remedy. Further information on the types of data useful for monitoring and evaluating natural attenuation performance can be found in the Office of Research and Development (ORD) publications EPA 1994a, 1997, 2004, 2011, and 2012, which are listed in the

“References” section of this document. In addition, the EPA published a detailed document on collection and evaluation of performance monitoring data for pump and treat (P&T) remediation systems that might be useful as a framework to evaluate MNA remedies (1994b).

The frequency of sampling and evaluation should be established on remedy selection and may be adjusted over the course of the entire performance monitoring period, as appropriate, to ensure MNA is progressing as expected. Sampling and evaluation frequency may be higher when first beginning performance monitoring, as it is important to have confidence in the rate(s) of attenuation. The frequency may decrease if observed data and trends are progressing as expected. Near the end of the performance monitoring stage, the sampling and evaluation frequency should generally increase again to support the data needs for the statistical evaluations required to progress to completion (EPA 2014a).

Contingency Remedies

The EPA recommends evaluating MNA remedies to determine the need for including one or more contingency measures that would be capable of achieving remedial objectives. Contingency remedies should generally be included as part of an MNA remedy, when MNA is selected based primarily on predictive analyses rather than on documented trends of decreasing contaminant concentrations. Contingency remedies should also generally be flexible—allowing for the incorporation of new information about site risks and technologies (EPA 1999).

The EPA recommends that one or more criteria (“triggers”) be established, as appropriate, in the remedy decision document that will signal unacceptable performance of the selected remedy and indicate when to implement contingency remedies. Such criteria should generally include, but not be limited to, the following:

- Contaminant concentrations in soil or groundwater at specified locations exhibit an increasing trend not originally predicted during remedy selection;
- Near-source wells exhibit large concentration increases indicative of a new or renewed release;
- Contaminants are identified in monitoring wells located outside of the original plume boundary;
- Contaminant concentrations are not decreasing at a sufficiently rapid rate to meet the remediation objectives; and
- Changes in land and/or groundwater use will adversely affect the protectiveness of the MNA remedy (EPA 1999).

In establishing triggers or contingency remedies, however, care is needed to ensure that sampling variability or seasonal fluctuations do not unnecessarily trigger a contingency. For example, an anomalous spike in dissolved concentration(s) at a well(s) might not be a true indication of a change in trend (EPA 1999). A thorough understanding of site conditions will more likely result in a more accurate or expected result.

Section 5: Completion Monitoring and Evaluation

Associated section of the MNA Checklist: Section 5. Completion Monitoring and Evaluation

The interval between sampling events (the sampling frequency) and the timeframe when data are collected generally should be based on site-specific groundwater flow conditions (such as hydraulic conductivity and gradient), seasonal variations, and other contributing factors. It may be appropriate to reevaluate the groundwater monitoring plan as the monitoring well data evaluation indicates that the remedial action is approaching cleanup levels for all contaminants of concern (COCs), particularly if a long sampling interval (for example, MNA sampling greater than 5-year frequency) has been employed. Monitoring frequency should ensure that sufficient data are available for both the remediation monitoring phase and the attainment monitoring phase evaluations, and at the same time should avoid unnecessarily long timeframes between sampling events. Many sites use quarterly sampling for evaluating groundwater monitoring well data. The sampling frequency used should ensure a representative sample of the aquifer's conditions, with the shortest sampling interval recommended being monthly (provided it is sufficient to document groundwater performance over time).

Rather than a single sampling event, a minimum number of data points is recommended (i.e., 4–8; EPA 2014b) to evaluate MNA completion status. This recommendation is based on existing groundwater behavior and statistical confidence (e.g., 95% upper confidence limit [UCL]) and is designed to ensure that decisions are made with sufficient supporting information.

It is recommended that groundwater monitoring well data sets and other related subsurface information be evaluated and compared against the CSM when making the decision whether sufficient groundwater monitoring well data has been collected.

Remediation Monitoring Phase

As discussed in the *Guidance for Evaluating Completion of Groundwater Restoration Remedial Actions* (EPA 2013), the remediation monitoring phase refers to the phase of the remedy when either active or passive remedial activities are being implemented to reach groundwater cleanup levels selected in a decision document.

Because the remediation monitoring phase is not the final decision point for completing the restoration remedial action in a particular well, the determination that MNA is effectively progressing toward restoration may be made using a visual or statistical (trend test or mean test) evaluation (EPA 2014b). Therefore, the EPA recommends that a minimum of four data points be used for analyses performed during this phase (EPA 2014b). Per the *Guidance for Evaluating Completion of Groundwater Restoration Remedial Actions*, the remediation monitoring phase completion typically occurs when the data collected and evaluated demonstrate that the groundwater has reached cleanup levels for all COCs, as they are stated in the Record of Decision (EPA 2013).

Completion of the remediation monitoring phase will help determine when the attainment monitoring phase can begin.

Attainment Monitoring Phase

The attainment monitoring phase typically begins after determining that the remediation monitoring phase is complete and cleanup levels have been achieved for all monitoring points. The attainment monitoring phase at a monitoring well is considered complete when contaminant-specific data provide a technical and scientific basis that:

- The contaminant cleanup level for each COC has been met (EPA 2014a, p. 9).
- The groundwater will continue to meet the contaminant cleanup level for each COC in the future (EPA 2014a, p. 9).

To achieve completion of the attainment monitoring phase, the EPA recommends a more robust data set using a visual or statistical (trend test and mean test) evaluation or tool to make the final attainment determination. Therefore, the EPA recommends that a minimum of eight data points (e.g., a minimum of four Remediation Monitoring Phase plus a minimum of four additional Attainment Monitoring Phase) be used for analyses performed during this phase for MNA remedies (EPA 2014b).

For both remediation and attainment monitoring phases, the recommended minimum number of data points, regardless of the statistical tool, should support the reliability of the tool and increase confidence in the results if statistical tools will be used for data evaluation. Although these minimum numbers of data points are recommended as a general matter, site conditions and the statistical tools, if utilized, may help establish the appropriate number of data points for the evaluation of both phases (EPA 2014b, p. 3).

Additionally, the updated Groundwater Statistics Tool (EPA 2018a, 2018b) evaluates COC concentrations on a well-by-well basis to help determine whether a groundwater restoration remedial action is complete. The use of a statistical tool is designed to support the *Guidance for Evaluating Completion of Groundwater Restoration Remedial Actions* (EPA 2013) and comports with principles outlined in the *Recommended Approach for Evaluating Completion of Groundwater Restoration Remedial Actions at a Monitoring Well* (EPA 2014b). A visual determination of the data may be used to generally conclude that the completion has been achieved if the data meets the criteria laid out in the 2014 EPA guidance (EPA 2014b).

MNA Special Considerations for Groundwater Completion Determinations

Generally, the physical and chemical behavior of an aquifer is not as perturbed by a passive system, such as MNA, as by an active system (e.g., P&T and ISCO). In the case of MNA, changes in groundwater flow velocities, flow paths, or geochemistry typically will be minimally affected, if at all, compared to when active technologies are employed. In the case of passive systems, when it is determined that the remediation phase is complete (with a recommended minimum of four data points, although more may be necessary for sufficient confidence), it may be appropriate to include the data used to support completion of the remediation monitoring phase as part of the attainment monitoring phase evaluation (for example, to obtain the recommended minimum of eight data points). In practice, when MNA is employed at a site, the data used to inform the remediation phase completion conclusion may also be useful as part of the attainment phase evaluation since active systems are not being employed.

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Attachments

Attachment 1: MNA Checklist

Attachment 2: Glossary

Attachment 1: MNA Checklist

Section 1. Site Conditions and Conceptual Site Model [EPA 1999, p. 14; EPA 2015, 1.3]

1.1. Background Information

- ☐ Identify historical site activities
- ☐ Identify existing/potential human health and ecological receptors
- ☐ Identify groundwater classification
- ☐ Identify any nearby public or private water supply wells
- ☐ Identify potential (preferential) transport pathways from the site that could adversely affect drinking water supplies
- ☐ Identify the presence of any wellhead protection areas
- ☐ Identify nearby surface water bodies that may be affected by plume migration
- ☐ Identify an updated (current) list of response actions

1.2. Geologic and Hydrologic Information

- ☐ Provide a detailed description of regional and site geology
- ☐ Identify any complex site geology that may preclude or inhibit adequate monitoring of a natural attenuation remedy
- ☐ Identify the physical, chemical, and biological properties of subsurface materials
- ☐ Identify local stratigraphy that may provide preferential pathways for, or barriers to, contaminant transport:
  - ☐ Thickness
  - ☐ Lateral extent
  - ☐ Continuity of units
  - ☐ Depositional features (e.g., channel deposits)
- ☐ Identify primary and secondary porosity features (e.g., fractures, karst features, matrix diffusion), permeability, and hydraulic conductivity of major stratigraphic units
- ☐ Provide historic and current depth to groundwater information
- ☐ Determine/identify the horizontal and vertical hydraulic head distribution (e.g., 3D visualization, potentiometric maps)
- ☐ Determine spatial and temporal measurements of hydraulic head
- ☐ Identify groundwater flow direction and magnitude (temporal and spatial) variability due to natural and/or engineered factors such as:
  - ☐ Seasonal fluctuations (e.g., rainfall, irrigation)
  - ☐ Influence from groundwater extraction or recharge
  - ☐ Short- or long-term changes due to urbanization or other construction-related or industrial factors (e.g., mining, oil and gas extraction)
  - ☐ Seasonal and total annual precipitation, spatial patterns of recharge, frequency, magnitude, and duration of severe storms, droughts, significant changes to range and variability in atmospheric temperatures, change in nearby surface water levels
  - ☐ or other factors that may influence MNA biological and physical processes, attenuation rates, and monitoring effectiveness
- ☐ Determine if the contaminant plume is currently/potentially discharging to surface water and/or surface seeps and springs or underflowing surface water bodies
- ☐ Identify any natural or engineered preferential pathways, such as buried channel deposits or sewer lines or utility conduits and backfilled trenches present at/near the site

☐ Identify vapor intrusion pathways and receptors

☐ Provide detailed hydrogeologic representations (e.g., cross sections, 3-D visualization) in transverse and longitudinal orientations with respect to groundwater flow directions showing the geology, wells, and plume concentrations

☐ Reference all historical U.S. Geological Survey, state agencies, or other peer-reviewed published studies/reports that include the vicinity of the site and provide their relevant findings

1.3. Source Control and Release Information

☐ For radionuclides: Identify the specific isotopes and associated daughter products present in site groundwater; include both in the assessment of plume stability [EPA 2015, 1.8] as well as decay rates (half-lives; T 1/2) and daughter products

☐ For organics: Determine/identify pathways, intermediates, products that may be as/more toxic and/or volatile and mobile than the parent contaminant present at the site (e.g., degradation of tetrachloroethylene to vinyl chloride) [EPA 1999, p. 6]

☐ For inorganics: Determine/identify specific mechanism (sorption, redox reactions, etc.) to assess stability of immobilized contaminants [EPA, 1999 p. 8; EPA 2015, p. 11]

☐ Identify the locations, depths, volumes, and nature and extent of past contaminant releases or sources

☐ Identify the vertical and lateral nature of current and future extent of the source zone

☐ Determine if the source zone contains free-phase (mobile) or residual (non-mobile) non-aqueous phase liquids (NAPLs)

☐ Identify source zone components and/or chemicals that may affect fate and transport of contaminants of concern (COCs) (presence of surfactants, high concentration of dissolved salts, multiphase mixtures, etc.)

☐ Identify any remedial or other activities at the site that may affect natural attenuation

☐ Identify if multiple plumes and/or commingled plumes are present at the site

☐ Identify any current or potential off-site contaminant contributions to the plume

☐ Identify specific flow pathway or paths from the source area to the downgradient limits of the contaminant plume or to receptors

☐ Identify any structural features resulting in source migration direction differing from groundwater flow direction

1.4. Site-Specific Geochemical Groundwater Data

Additional groundwater geochemical conditions to support MNA [EPA 2015, 4.4]. Select all that apply:

☐ pH

☐ Oxidation-reduction potential

☐ Conductivity

☐ Dissolved oxygen

☐ Dissolved organic carbon and dissolved inorganic carbon

☐ Concentration and identification of major cations and anions

☐ Chemical speciation of the contaminants and key reactants in groundwater

☐ Ferrous iron and Sulfide

☐ Methane/ethane/ethene

☐ Turbidity

☐ Biogeochemistry of groundwater and soil

☐ Other:

Section 2. Remedy Selection Considerations

2.1. Sites Where Monitored Natural Attenuation May Be Appropriate [EPA 1999, p. 17–19]

- ☐ Identify if all the contaminants present in soil and/or groundwater can be effectively remediated by natural attenuation processes
- ☐ Identify contaminant plume stability
- ☐ Identify potential for the environmental conditions (i.e., geochemistry) that influence plume stability to change over time
- ☐ Identify any human health, drinking water supplies, groundwater aquifers, surface waters, ecosystems, sediments, air, or other environmental resources that could be adversely impacted as a consequence of selecting MNA as the remedial option
- ☐ Identify current and projected demands for the affected resource over time
- ☐ Identify if the contaminant(s), either by itself or as an accumulation (e.g., comingling) with other nearby sources (on site or off site), will exert a long-term detrimental impact on available water supplies or other environmental resources
- ☐ Identify if the estimated timeframe of remediation is reasonable (see section on “Considerations for a Reasonable MNA Timeframe”)
- ☐ Identify the nature and distribution of contaminant sources and whether these sources have been, or can be, adequately controlled
- ☐ Identify if the resulting transformation products present a greater risk, due to increased toxicity and/or mobility, than the parent contaminants
- ☐ Identify the impact of existing and proposed active remedial measures (e.g., pumping wells and physical/chemical/biological treatments) on the MNA component of the remedy
- ☐ Identify if reliable site-specific mechanisms for implementing institutional controls (ICs) (e.g., zoning ordinances) are available, and if an institution responsible for their monitoring and enforcement can be identified/established
- ☐ Identify if existing data supports MNA throughout the plume or only for a portion of the plume

2.2. Considerations for a Reasonable MNA Timeframe [EPA 1999, p. 2, 19–20; EPA 2015, 2.6]

- ☐ Determine the beneficial use designation of the groundwater aquifer system (e.g., drinking water source, agricultural water source)
- ☐ Determine reliability of monitoring and of ICs over the selected period of performance
- ☐ Determine public acceptance of the timeframe required to reach remediation objectives
- ☐ Ensure adequate funding is in place for monitoring and performance evaluation over the selected period of performance required for remediation
- ☐ Identify that site-specific assumptions as part of the conceptual site model are included to assist with restoration timeframe evaluations
- ☐ Identify uncertainties surrounding all site-specific assumptions (e.g., mass and flux of contaminants, source strength)
- ☐ Determine if the MNA timeframe is comparable with other active remedy timeframes
- ☐ Determine how uncertainties surrounding all site-specific assumptions may extend the estimated MNA timeframe
- ☐ Determine if demographic factors such as population growth (or decline) rates have been evaluated and the impact on aquifer behavior (e.g., capture zone, travel time)

Section 3. MNA Evaluation and Selection

3.1. First Line of Evidence – Plume Stability

- ☐ Identify historical groundwater and/or soil chemistry data that demonstrate a statistically significant trend of decreasing contaminant mass and/or concentration over time at appropriate monitoring or sampling points
- ☐ Provide time-series statistical evaluation for individually sampled wells (e.g., minimum of four sampling events at a sampling frequency of no less than quarterly)
- ☐ Perform a time-series contaminant concentration analysis in groundwater to show trend statistical significance
- ☐ Identify/determine the areal and vertical extent of plume (i.e., shrinking or expanding)
- ☐ Determine current and future subsurface physical and chemical conditions and their spatial and temporal variations within the aquifer

3.2. Second Line of Evidence – Natural Attenuation Process

3.2.1. Determine Primary Mechanism

Microbial Degradation [EPA 2015, 5.1]

- ☐ Identify appropriate microbial consortia
- ☐ Identify if sufficient microbial population (e.g., bacteria, fungi) is present in part or all of the affected groundwater plume
- ☐ Identify any genomics tests supporting degradation activity (e.g., enzymatic activity)
- ☐ Identify terminal electron acceptors (i.e., O_2, NO_3 , Mn(IV), Fe(III), SO_4 , CO_2) critical for biological and chemical degradation of contaminants (e.g., benzene, toluene, ethyl benzene, and xylene)" (Huling et al., 2002)

Chemical Redox Transformations and Hydrolysis [EPA 2015, 5.2]

- ☐ Identify change in oxidation state (Fe^{2+}/Fe^{3+}) abiotic or microbially mediated
- ☐ Determine if transformation is permanent (thermodynamically stable or kinetically slow)
- ☐ Determine if the transformation rates of daughter products are understood and quantifiable
- ☐ Identify whether shifts in groundwater pH or bulk geochemistry will affect the metals solubility and reversibility in the attenuation process
- ☐ Identify terminal electron acceptors (i.e., O_2, NO_3^-, Mn(IV), Fe(III), SO_4^{2-}, CO_2) critical for biological and chemical degradation of contaminants (e.g., benzene, toluene, ethyl benzene, and xylene)" (Huling et al., 2002)

Sorption and Precipitation [EPA 2015, 5.3]

- ☐ Determine if there is sufficient evidence to quantify the partitioning of contaminants to the soil/geologic matrix
  - ☐ Density
  - ☐ Henry's Law constant
  - ☐ Vapor pressure
  - ☐ Effective solubility
  - ☐ Octanol-water portioning coefficient
  - ☐ Dissociation constant
- ☐ Determine if contaminant ions are precipitating as a pure phase or co-precipitating within the structure of another mineral phase
- ☐ Compare the equilibrium solubility constant for a given solid-phase mineral to the ion activity product

Radioactive Decay [EPA 2015, 5.4]

- ☐ Determine if radioactive decay is the primary attenuating process (i.e., radon and/or tritium) or is working in conjunction with other attenuating processes

☐ Determine if the decay rates of daughter products are understood and quantifiable
☐ Determine if the decay rates of daughter products are less than the decay rate for the parent
☐ Determine if there is a build-up (increase) of daughter products
  ☐ If yes, is it causing ingrowth?

Other Mechanisms

☐ Dilution (not preferred)
  ☐ Dilution resulting from groundwater mixing with a surface water body is not acceptable as a line of evidence
☐ Dispersion (not preferred)
☐ Volatilization
  ☐ Evaluate transport or partitioning to the vapor phase

3.2.2. Determine Rate of Attenuation

Calculation and Use of First-Order Rate Constants for Monitored Natural Attenuation Studies (EPA 2002) discusses the following two methods to determine rate estimates: [EPA 2015, 4.2– 4.5]

☐ Determine plume concentration vs. distance from a source (horizontally and vertically)
☐ Determine plume concentration vs. time at individual wells

3.3. Third Line of Evidence – Attenuation Capacity (Microcosm Studies)

☐ Determine if biodegradation is occurring and quantify rates and pathways
☐ Determine if observed redox conditions are compatible with predicted biodegradation mechanisms and assumptions
☐ Characterize and evaluate current and future microbial growth conditions (e.g., nutrients and terminal electron accepters)
☐ Characterize concentrations of co-metabolites and metabolic byproducts
☐ Identify other contaminants that would out-compete the primary COC by the microbes
☐ Identify reasonable estimates of the biodegradation rate constants and kinetic parameters
☐ Determine if observed redox conditions are appropriate for all chlorinated volatile organic compounds (CVOCs), including daughter products
☐ Determine if redox conditions will change spatially or over time
☐ Identify if the degradation process could stall (e.g., cis-1,2-DCE and vinyl chloride)
☐ Evaluate the potential for problematic increases in toxic breakdown products
☐ Determine if the degradation rate is reduced for toxic breakdown contaminants
☐ Identify if the complete degradation sequence of breakdown products requires a variety of oxidation states in the aquifer
☐ Identify data to support the appropriate redox zonation

3.4. Contaminants of Concern

Petroleum-Related Contaminants [EPA 1999, p. 7]

☐ Identify the potential for remaining benzene, toluene, ethylbenzene and xylene (BTEX) residue consisting of heavier petroleum hydrocarbons to persist well after MNA has achieved remedial goals for primary COCs
☐ Identify if in situ residual petroleum source mass sustains undesirable conditions in the aquifer (e.g., high total dissolved solids or anoxic conditions)
☐ Identify if these conditions will adversely affect current water supplies or potential future beneficial use of the aquifer
☐ Identify what source control measures will be taken to remediate or otherwise address the residual contaminant mass

Chlorinated Solvents [EPA 1999, p. 7]

- ☐ Identify if observed redox conditions are appropriate for all CVOCs, including daughter products
- ☐ Identify the potential for the degradation process to stall (e.g., current data or potential conditions)
- ☐ Identify the potential for problematic increases in toxic breakdown products (e.g., current data or potential conditions)
- ☐ Identify if the complete degradation sequence of breakdown products requires a variety of oxidation states in the aquifer
- ☐ Identify data to support the appropriate redox zonation

Inorganics/Radionuclides [EPA 1999, p. 8]

- ☐ Identify aquifer mineralogy information and solid-phase contaminant speciation
- ☐ Identify the contaminant immobilization processes (EPA 2007a) for inorganic contaminants [EPA 2015, 4.4]
- ☐ Characterize soil/geologic matrix [EPA 2015, 4.5] [EPA 2015, Appendix B]
  - ☐ Mineralogy (e.g., X-ray diffraction, X-ray fluorescence)
  - ☐ Cation Exchange Capacity (CEC)
  - ☐ Total Organic Carbon (TOC)
  - ☐ Acid Volatile Sulfides (AVS)/Simultaneously Extracted Metals (SEM)
  - ☐ Sequential extraction procedures (SEP)
  - ☐ Geochemical speciation analysis for determining the redox conditions of the aquifer
  - ☐ Laboratory batch and flow-through column tests for determining the sorption capacity of the aquifer materials
- ☐ Determine aquifer capacity for contaminant attenuation
  - ☐ Laboratory batch tests
  - ☐ In situ batch tests
  - ☐ Flow-through column tests
  - ☐ Geochemical models (not preferred when used as sole criteria)

Section 4. Performance Monitoring and Evaluation

- ☐ Determine evaluation frequency of wells or other components of the long-term monitoring network for integrity and functionality
- ☐ Identify number and location of sentinel wells that would allow sufficient time for a response action to protect receptors
- ☐ Identify ICs to ensure that development activities do not encroach into affected or potentially affected areas
- ☐ Ensure performance monitoring will continue until remedial objectives have been achieved, and longer, if necessary, to verify that the site no longer poses a threat to human health or the environment
- ☐ Identify plans for periodic sampling of aquifer solids (e. g., through soil coring); sampling of solid- phase materials generally may be warranted at many sites to evaluate potential reduction in the capacity of aquifer materials, over time, to immobilize contaminants [EPA 2015, 2.3]
- ☐ Evaluate any potential changes in environmental conditions (e.g., hydrogeologic, geochemical, redox zones, microbiological, or other changes) that may reduce the efficacy of the natural attenuation processes
- ☐ Identify new or previously unknown releases of contaminants to the environment that could impact the effectiveness of the natural attenuation remedy

- ☐ Verify no unacceptable impact to downgradient receptors
- ☐ Demonstrate the efficacy of ICs to protect potential receptors
- ☐ Verify that the plume(s) is not expanding (e.g., downgradient, laterally, or vertically)
- ☐ Identify any new potentially toxic and/or mobile transformation products post MNA selection
- ☐ Determine if MNA performance is consistent with original MNA remedy selection metrics and projected trends
- ☐ Conduct monitoring at specified intervals

Contingency Remedy [EPA 1999]

- ☐ Select appropriate contingency remedy tailored to site-specific characteristics
- ☐ Identify triggers for selected contingency remedy
- ☐ Monitor triggers for implementation of contingency remedy

Section 5. Completion Monitoring and Evaluation

Remediation Monitoring Phase [EPA 2014a, EPA 2014b]

- ☐ Determine if the remediation monitoring phase has been completed
  - ☐ Determine if the 95% upper confidence limit (UCL) has achieved the cleanup level
  - ☐ Determine if there is a statistically significant zero or negative slope trend
  - ☐ Recommend a minimum of four data points for the remediation monitoring phase completion evaluation

Attainment Monitoring Phase [EPA 2014a, EPA 2014b]

- ☐ Determine if the contaminant cleanup level for each COC have been achieved
  - ☐ Determine if the 95% UCL has achieved the cleanup level
  - ☐ Determine if there is a statistically significant zero or negative slope trend
  - ☐ Recommend a minimum of eight data points for the attainment monitoring phase completion evaluation
- ☐ Determine if the groundwater will continue to meet the contaminant cleanup level for each COC in the future

Attachment 2: Glossary

95 UCL: A value that, when calculated repeatedly for randomly drawn subsets of site data, equals or exceeds the true mean 95% of the time.

Abiotic degradation: The process by which a substance is converted to simpler products by chemical (nonbiological) mechanisms, for example, hydrolysis.

Absorption: The process by which atoms, molecules, or ions enter a bulk phase (liquid, gas, solid).

Adsorption: The adhesion of molecules of gas, liquid, or dissolved solids to a surface.

Aerobic: Pertaining to or caused by the presence of oxygen.

Anaerobic: Pertaining to or caused by the absence of oxygen.

Aquifer: A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells or springs.

Aquifer, confined: An aquifer bounded above and below by impermeable beds or by beds of distinctly lower permeability than that of the aquifer containing confined groundwater.

Aquifer, unconfined: An aquifer in which there are no confining beds between the zone of saturation and the ground surface. There will be a water table in an unconfined aquifer.

Attenuation: A variety of physical, chemical, or biological processes that, under favorable conditions, act to reduce the mass, toxicity, mobility, volume, or concentration of contaminants in soil or groundwater.

Back diffusion: The transfer of the contaminant of concern from lower permeability zones back to the higher permeability zones because of the reversal of the concentration gradient, typically after the source flux is near zero; also referred to as reverse diffusion.

Bedrock: The consolidated rock that underlies unconsolidated soils and glacial debris.

Biodegradation: A natural process during which microorganisms break down chemicals into less complex compounds.

Bioremediation: The treatment of environmental contamination through the use of techniques that rely on biodegradation. Bioremediation has two essential components: biostimulation and bioaugmentation.

Class I aquifer: Aquifers that are classified as “special groundwater.” These aquifers have one or more of the following characteristics:

- Contain resources of unusually high value that are highly vulnerable to contamination.
- Are an irreplaceable source of drinking water that serves a substantial population or are where alternative drinking water sources are economically infeasible.
- Are ecologically vital and supply a sensitive ecological system that supports a unique habitat.

Class IIA aquifer: An aquifer that is used as a current source of drinking water.

Class IIB aquifer: An aquifer that is a potential source of drinking water based on the following criteria:

- Has a salinity less than 10,000 mg/L total dissolved solids.
- Can be used without treatment or treated with methods found in a public water system.
- Can yield at least 150 gallons/day.

Compliance monitoring: The collection of data that, when analyzed, can allow for the evaluation of the contaminated media against standards such as soil or water quality regulatory standards, risk-based standards, or remedial action objectives.

Conceptual site model: A representation of an environmental system and the biological, physical, and chemical processes that determine the transport and fate of contaminants through environmental media to environmental receptors and their most likely exposure modes.

Daughter products: Also known as transformation products, these intermediate products result from biotic or abiotic processes *(*e.g., TCE, DCE, vinyl chloride), decay chain daughter products from radioactive decay, and inorganic elements that become methylated compounds *(*e.g., methyl mercury) in soil or sediment. Some transformation products are quickly transformed to other products while others are longer lived.

Degradation: The transformation of one chemical to another by such processes as hydrolysis, photolysis, and biodegradation.

Desorption: The process in which atomic or molecular species leave the surface of a solid and escape into their surroundings.

Destruction: The breakdown of a chemical constituent into a new chemical form.

Dilution: The process of decreasing the liquid phase contaminant of concern concentration through in situ mixing with noncontaminated groundwater.

Dispersion: The phenomenon by which a contaminant of concern in flowing groundwater mixes with uncontaminated water, becoming reduced in concentration. Dispersion is due both to differences in water velocity at the pore level and differences in the rate at which water moves through different strata. It also refers to statistical measures of how widely a set of data varies.

Downgradient: In the direction of decreasing hydrostatic head.

Hydraulic conductivity: The ability of an aquifer to transmit water. Aquifers with high hydraulic conductivity yield and transmit more water than similar aquifers with low hydraulic conductivity.

Inorganic compounds: Metals, salts, and various nonbiological carbon species (e.g., carbon monoxide, carbon dioxide). These compounds do not combust in incinerators.

Lines of evidence: Site-specific information collected to provide a specified level of confidence on the estimates of attenuation rates and remediation timeframe to evaluate potential efficacy of MNA.

Monitored natural attenuation: A remedy that relies on natural processes (i.e., biodegradation, sorption, dilution, evaporation, and chemical reactions), without human intervention, to decrease or "attenuate" the concentration of contaminants in soil and groundwater. Scientists monitor these conditions to confirm that natural attenuation is occurring. Monitoring typically involves collecting soil and groundwater samples to analyze them for the presence of contaminants and other site characteristics.

Non-aqueous phase liquid: Hydrocarbons that exist as a separate, immiscible phase when in contact with water and/or air. There are two types of NAPLs, light non-aqueous phase liquids (LNAPLs) and dense non-aqueous phase liquids (DNAPLs). LNAPLs are less dense than water and tend to float on the water table (e.g., gasoline). DNAPLs have a density greater than water.

Organic compounds: A large class of chemical compounds in which one or more atoms of carbon are covalently linked to atoms of other elements, most commonly hydrogen, oxygen, or nitrogen.

Plume: A defined area of contaminated groundwater or soil gas.

Radioactive decay: A radioactive process in which a nucleus undergoes spontaneous transformation into one or more different nuclei and simultaneously emits radiation, loses electrons, or undergoes fission.

Reasonable timeframe: A timeframe comparable to that which could be achieved through active restoration. This site-specific decision must be determined through an analysis of alternatives. To ensure that these estimates are comparable, assumptions should be consistently applied for each alternative considered.

Receptor: Any organism—including site employees, building occupants, the public at large, the atmosphere, animals, plants, and microorganisms—that may be affected by a release of a contaminant or pollutant.

Recharge: Water that moves from the land surface or unsaturated zone into the saturated zone.

Sentinel well: A groundwater monitoring well situated between a sensitive receptor downgradient and the source of a contaminant plume upgradient. Contamination should be first detected in the sentinel well, which serves as a warning that contamination may be moving closer to the receptor. The sentinel well should be located far enough upgradient of the receptor to allow enough time before the contamination arrives at the receptor to initiate other measures to prevent contamination from reaching the receptor, or in the case of a supply well, provide for an alternative water source.

Sorption: Movement of a substance from the aqueous phase to the solid phase, whether by adsorption, absorption, fixation, or precipitation. Sorption may be reversible or irreversible.

Source control: Those efforts that are taken to eliminate or reduce, to the extent practicable, the release of contaminants of concern from direct and indirect ongoing sources to the aquatic system being evaluated.

Source material: Material that includes or contains hazardous substances, pollutants, or contaminants that act as a reservoir for migration of contamination to ground water, to surface water, to air, or acts as a source for direct exposure.

Stabilization: A cleanup method that prevents or slows the release of harmful chemicals from wastes by converting the constituents into a less soluble, mobile, or toxic form. These methods usually do not destroy the contaminants.

Stable: Describes a plume boundary that is not expanding or migrating and that has concentrations that are not increasing. In determining whether a plume is stable or migrating, users of this document should consider the uncertainty associated with defining the limits of contaminant plumes. For example, a plume is typically delineated for each contaminant of concern as a two- or three-dimensional feature.

Plumes are commonly drawn by computer contouring programs that estimate concentrations between actual data points. The EPA recognizes that a plume boundary is more realistically defined by a zone rather than a line. Fluctuations within this zone are likely to occur because of a number of factors (e.g., analytical, seasonal, spatial), which may or may not be indicative of a trend in plume migration. Therefore, site characterization activities and performance monitoring should focus on collection of data of sufficient quality to enable decisions to be made with a high level of confidence. [EPA 1999, p. 18]

T 1/2: Half-life; indicates the time required to reduce the concentration by 50% from any concentration point in time.

Transformation: When a parent substance is converted by chemical and/or biological processes into a degradation or formation product.

Transformation (chemical): An abiotic or biotic chemical process (such as photolysis, hydrolysis, oxidation/reduction, radioactive decay) that transforms an element (e.g., Cr(VI) to Cr III) or compound (e.g., phenol to $CO_2 + H_2O$) to a different element or chemical compound.

Volatile organic compound: Any organic compound that evaporates readily to the atmosphere.

Volatilization: The conversion of a liquid or solid phase into a vapor phase.