Soil and groundwater assessments performed during site investigations

Guidance Document 4-01 Petroleum Remediation Program

This document describes the requirements for completing soil and groundwater assessments during a site investigation. All site investigations begin as a limited site investigation (LSI) but may proceed to a remedial investigation (RI). The LSI evaluates risk based on a quick assessment of current site conditions. An objective of the LSI is to identify low-risk sites where further investigation or corrective action is not necessary. The information collected during the LSI helps determine whether an RI is necessary. An RI measures groundwater contaminant concentrations in monitoring wells over time to establish plume stability.

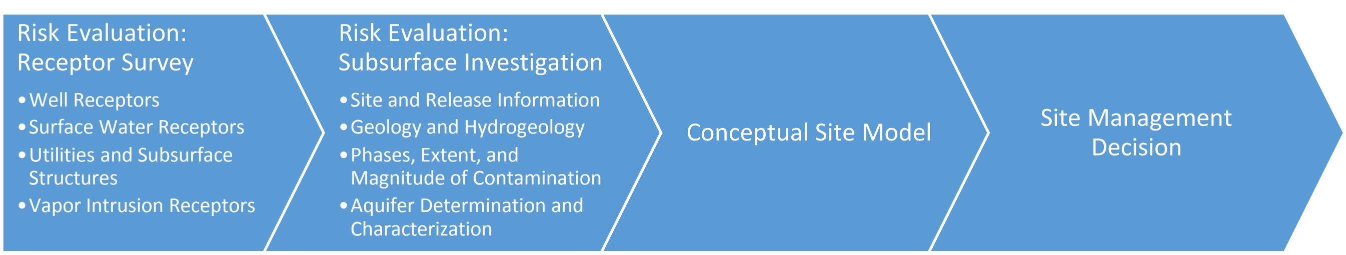
The Minnesota Pollution Control Agency (MPCA) encourages completing the receptor surveys described in Risk Evaluation and Site Management Decision at Petroleum Release Sites prior to initiating the soil and groundwater assessments. Identifying receptors and potential exposure pathways supports effective planning of soil and groundwater assessment activities. Risk is then evaluated by measuring the extent and magnitude of contamination with respect to identified receptors. Therefore, it is important to identify receptors ahead of any subsurface investigation.

Vapor intrusion assessment
A vapor intrusion assessment is also required during the site investigation. It is discussed in Vapor Intrusion Assessments Performed During Site Investigations.

I. Conceptual site model

The site investigation involves development of a conceptual site model (CSM). Soil, groundwater, and vapor intrusion assessment data, in conjunction with receptor survey results, are critical for developing the CSM. The following discussion provides the context for planning, completing, and evaluating results from a risk evaluation.

A CSM provides the framework for evaluating site-specific exposure pathways upon which site management decisions are based. The CSM integrates the various elements of the risk evaluation (subsurface investigation and receptor surveys) to assess potential exposure pathways in accordance with the Petroleum Remediation Program’s risk-based approach. Site management decisions are often based on multiple risks that must be considered collectively prior to making a comprehensive site management decision. Site management decisions may lead to additional investigation or corrective action that subsequently alters the CSM by addressing one or more of its elements. The Investigation Report is structured to facilitate development of the CSM. The elements outlined in the Investigation Report that need to be considered in developing the CSM are illustrated below.



The focus of the CSM should ultimately lead towards identifying any additional investigation, monitoring, or corrective action necessary to address exposure pathways, or towards justifying site closure. The CSM should not summarize or reiterate the various elements of the risk evaluation. A successful CSM focuses on the relationship between identified risks and the investigation results to identify site-specific exposure pathways. The CSM must demonstrate that all exposure pathways have been adequately investigated and any high risks have been addressed if site closure is recommended.

At the time the Investigation Report is submitted, it may not be possible to create a complete CSM based on the available data. The CSM is still necessary at this stage to identify additional data needs and to focus the investigation. As the site investigation progresses and corrective actions are implemented, the CSM must be updated and re-evaluated to support subsequent site management decisions.

The Investigation Report figures, particularly the cross sections, are essential for illustrating the pathway evaluation discussed in the CSM. Figures should depict significant relationships between risk evaluation elements.

An accurate CSM requires an understanding of the three-dimensional distribution and behavior of each of the four basic subsurface petroleum contaminant phases:

1. Light non-aqueous phase liquid
2. Aqueous phase
3. Vapor or gaseous phase
4. Adsorbed or solid phase

Within a relatively short time after a significant petroleum release, all four petroleum contaminant phases are usually present in the subsurface. Due to their differing physical and chemical properties, the four phases exhibit different subsurface behaviors. The subsurface behavior of the various phases is also affected by site-specific geology. Identifying exposure pathways for the various phases is fundamental to developing the CSM. Exposure pathway evaluation begins with receptor identification and delineating the extent and magnitude of contamination in relation to receptors.

Natural attenuation of petroleum releases is an important consideration of CSM development. Not all petroleum compounds behave similarly in the environment. Some compounds are resistant to biodegradation, an important natural attenuation process. Leaded gasoline additives, particularly 1,2-dibromoethane (EDB) and 1,2-dicholorethane (DCA), and the oxygenate methyl *tertiary*-butyl ether (MTBE) are synthetic, non-readily biodegradable compounds. They have higher aqueous solubility limits than naturally occurring, readily biodegradable petroleum compounds such as benzene. Releases of these synthetic compounds present an additional risk. They can travel farther and may persist in the environment longer than naturally occurring hydrocarbons. If these compounds are present, consider their behavior in the CSM and when making the site management decision.

II. Soil contamination assessment

A. Drilling methods

Preferred drilling methods include hollow-stem auger and sonic, or, for LSIs where conditions are appropriate, direct push. Do not use direct push when conditions at the site are likely to result in not meeting, or the technology had previously failed to meet, the drilling depth requirements. Do not use solid-stem flight augers for soil borings unless approved by the MPCA. Perform continuous soil sampling unless MPCA staff approve an alternative approach. For all borings, follow the procedures listed below:

1. Completely clean all down-hole equipment and tools prior to each use to avoid cross-contamination. Cleaning methods include power spray wash, brushing with appropriate cleaning solution, and clean water rinse.

2. Boreholes that are not completed as monitoring wells should be sealed in accordance with the Minnesota Department of Health well code (Minn. R. ch. 4725).
3. Complete a drilling log for every soil boring advanced. When monitoring wells are completed in a boring, provide well construction diagrams as described in Section III.B below. At a minimum, information in the logs should include:
    - Depth to start and finish of each soil sample interval attempted (feet).
    - Recovery for each soil sample interval attempted (feet).
    - Soil classification in accordance with the 1952 Unified Soil Classification System (USCS) or with American Society for Testing Materials (ASTM) test methods D2487 or D2488.
    - Further description of soil (grain size, sorting, color, geologic origin, etc.).
    - Depth of significant changes in material (feet).
    - Approximate depth to water below grade (feet); include date and time of measurement.
    - Soil headspace screening results in parts per million by volume (ppmv).
    - Comments regarding significant geologic and hydrogeologic features, visual and olfactory evidence of contamination, and petroleum sheen test results.
    - Depth to top and bottom of open hole or exposed screen if collecting water samples from an open boring or temporary well.
    - Date and time boring started and completed.
    - Date and time boring sealed.
    - Name of driller and consultant, as well as others present during drilling.
    - Drilling method.
    - Boring identification number.
    - Penetration test records, if applicable.
    - Ground surface elevation (feet, relative to identified datum). To establish ground surface elevation, survey all boring locations.

B. Drilling locations

1. Magnitude of soil contamination and source identification

Advance a soil boring in or immediately adjacent to all tank basins and tank components regardless if there is a known release associated with them. These include underground storage tank basins, aboveground storage tank basins, product transfer areas, piping, dispensers, remote fill pipes, valves, known release areas not previously assessed, and visibly stained areas.

2. Horizontal extent

Drill a sufficient number of soil borings to define the horizontal extent of soil contamination, keeping in mind that the most extensive soil contamination may not be near the ground surface. In general, the initial borings used to define the horizontal extent should not be drilled more than 50 feet from a source area. The number of borings will vary depending on site conditions, extent of contamination, and locations of receptors. Horizontal extent is considered defined in the field if there is no visual evidence of contamination, there are no petroleum odors, and soil headspace screening results (i.e., photoionization detector (PID) readings) are less than 10 ppmv. In addition to field-based evidence, extent is also defined by a soil analytical level of 100 mg/kg gasoline range organics (GRO) or diesel range organics (DRO). Complete additional borings when subsequent laboratory analysis indicates the extent has not been defined.

3. **Vertical extent**

   Drill soil borings to 5 feet below the water table or, if contamination extends below the water table, to 10 feet below the deepest measurable contamination, whichever is deeper. If the water table is very deep and you have drilled 10 feet below the deepest measurable contamination in the unsaturated zone, discontinue drilling. Vertical extent is considered defined in the field if there is no visual evidence of contamination, there are no petroleum odors, and PID readings are less than 10 ppmv. If bedrock is encountered, contact the MPCA to discuss whether bedrock monitoring wells are necessary.

   Examples:

   - If contamination extends to 10 feet and the water table is at 20 feet, advance the boring to 25 feet.
   - If contamination extends to 20 feet and the water table is at 15 feet, advance the boring to 30 feet.
   - If contamination extends to 20 feet and the boring has been advanced to 30 feet without encountering the water table, end the boring at 30 feet.

4. **Site stratigraphy**

   To evaluate site stratigraphy, complete at least one soil boring to 20 feet below the deepest site contamination. If the water table is encountered, at least one boring a minimum of 20 feet below the water table is necessary. If the water table is very deep and you have drilled 20 feet below the deepest site contamination in the unsaturated zone, contact the MPCA for approval to discontinue drilling deeper. Locate the soil boring near the suspected release point but not within an area of light non-aqueous phase liquid (LNAPL). If there is a risk of cross-contamination by piercing a confining unit, complete the boring in an uncontaminated area. If additional site stratigraphy data are available, the MPCA may waive this requirement with prior approval.

   Examples:

   - If contamination extends to 10 feet and the water table is at 20 feet, advance the boring to 40 feet.
   - If contamination extends to 25 feet and the water table is at 20 feet, advance the boring to 45 feet.
   - If contamination extends to 20 feet and the boring has been advanced to 40 feet without encountering the water table, then call the MPCA staff for approval to discontinue drilling deeper.

5. **Utility backfill investigation**

   If underground utilities (sanitary and storm sewer lines, water distribution lines, etc.) appear to intercept contaminated soil or groundwater, advance hand-driven or hand-augured soil borings in the utility backfill. The purposes of these soil borings are to investigate potential migration of LNAPL and contaminated groundwater within the backfill and to assess the potential for water line permeation. The backfill investigation is especially important when low permeability soil (e.g., clay) occurs near the surface.

C. Soil sampling

1. **Stratigraphy**

   Record geologic descriptions for all soil samples collected and note changing drilling conditions that provide relevant geologic and stratigraphic information. Be sure to note the presence and thickness of sand and gravel lenses within less permeable soils.

2. **Grain-size analysis**
Grain-size analysis is required at all sites to verify field classification of soils. In saturated conditions, grain-size analysis is required to estimate hydraulic conductivity. Collect a minimum of three soil samples from different locations/horizons. If groundwater is encountered, collect at least two of the samples below the water table from horizons that appear to have the highest hydraulic conductivity. If an apparent confining layer is encountered, collect an additional grain-size sample to characterize the soil. Record the depth of collected samples on the boring logs. Analyze samples using American Society for Testing Materials (ASTM) test method D422.

   If installing deep monitoring wells during an RI, collect additional soil samples for grain-size analysis to estimate the hydraulic conductivity at the depth of the screened interval.

3. **Soil headspace screening**
Collect and evaluate soil samples for organic vapors with a PID at least every 5 feet in uncontaminated soil, at changes in material, and at least every 2.5 feet in contaminated soil. Record the depth of collected samples and the PID readings on the boring logs. Soil headspace screening procedures are described in Soil Sample Collection and Analysis Procedures.

4. **Petroleum-saturated soil screening**
Use the petroleum sheen test described in Soil Sample Collection and Analysis Procedures to determine if soil is petroleum saturated. Collect and evaluate soil samples for petroleum sheen in contaminated soil with a PID reading of 10 ppmv or greater. Additionally, evaluate soil samples where other field evidence, such as staining, suggests residual LNAPL may be present. Record the depth of collected samples and the results on the boring logs.

5. **Laboratory analysis**
Select soil samples for laboratory analysis according to the guidelines in Table 1, and record the sampling depth on the boring logs. The objective of discrete soil sampling is to sample the interval that represents the most impacted horizon. Collect and analyze soil samples following the procedures and analytical requirements described in Soil Sample Collection and Analysis Procedures.

Table 1. Soil analytical sampling depths based on groundwater and contamination occurrence.

	No contamination	Contamination
No groundwater	Boring terminus	Highest PID reading and boring terminus
Groundwater	Water table	Water table and highest PID reading if not at the water table[1,2]

[1]If contamination extends more than ten (10) feet below the water table, collect groundwater samples below the water table according to Section III.A.1.

[2]If the highest PID reading occurs at the water table, only one soil sample is required.

6. **Surface soil assessment**

   The surface soil assessment is supplemental to standard soil headspace screening, petroleum-saturated soil screening, and laboratory analysis sampling described above. For soil borings completed in areas without an impervious surface, assess surface soil according to the following protocols:

   - Screen soil using soil headspace screening (PID readings), the petroleum sheen test, and visual observation of stained soil from the applicable depth interval(s) according to current land use: 0-2 feet for commercial and industrial, or 0-2 and 2-4 feet for residential.
   - Collect a soil sample for laboratory analysis from each interval where the PID reading is at or above the screening level (Table 2) or the soil is visibly stained. The sample should represent the most contaminated soil within the screened depth interval. A soil sample is not required, however, when the petroleum sheen test result is positive, regardless of PID reading or staining. Analyze samples for GRO and/or DRO according to Table 3.

Table 2. Surface soil headspace screening levels (PID readings).

Petroleum product	Screening level (ppm)
Gasoline, ethanol-blended fuel, and aviation gasoline	40
Diesel fuel, fuel oil, used or waste oils, jet fuel, kerosene	10

Table 3. Surface soil analytical requirements.

Petroleum product	Required analysis
Gasoline and aviation gasoline	GRO
Diesel fuel, fuel oil, used or waste oils, jet fuel, kerosene	DRO
Unknown petroleum or hydrocarbons mixture	GRO and DRO

Surface soil sampling results are reported in the Investigation Report. See Risk Evaluation and Site Management Decision at Petroleum Release Sites for the criteria used to define surface soil as contaminated. When contaminated surface soil is identified during the site investigation, provide recommendations for delineating the extent of surface soil contamination in the Investigation Report.

Delineating the extent of contaminated surface soil after the site investigation is necessary prior to approving a corrective action. Delineation after the site investigation is completed using the same procedures and criteria described above. Sampling locations are generally based on a grid pattern with 20-foot node spacing in areas where contaminated surface soil was identified during the site investigation. Additional laboratory analyses may be required for soil treatment or disposal as described in Soil Sample Collection and Analysis Procedures.

7. **Water levels**
   Measure the water level in all borings and compute groundwater elevations. Record the time at which measurements are made. Inspect soils for evidence of a fluctuating water table and a seasonal high water table (i.e., mottling). If soil borings in silt or clay appear unsaturated, record on the boring log the amount of time the boring was left open to allow measurement of the water level. Borings may be left open up to 72 hours to facilitate accurate water level measurements and collection of groundwater samples.

8. **LNAPL**

   If mobile LNAPL is found during boring advancement, notify the Minnesota Duty Officer (651-649-5451 or 1-800-422-0798) within 24 hours and immediately begin LNAPL recovery. Install permanent monitoring wells as soon as possible to define the extent of mobile LNAPL. If there are questions about whether to convert a boring to a monitoring well when mobile LNAPL is discovered or appears likely to be present, contact the MPCA to discuss. Refer to Light Non-Aqueous Phase Liquid Management Strategy for additional information.

III. Groundwater contamination assessment

A. Limited site investigations

At sites where contaminated soil is in contact with groundwater, or groundwater contamination appears likely, a groundwater contamination assessment is necessary as part of the LSI. The objectives of the assessment are to determine whether groundwater is, or likely to be, impacted; whether the impacted hydrogeologic unit is considered an aquifer; and, if groundwater is impacted, the magnitude and horizontal extent of the impacts. Horizontal extent is considered defined when contamination at the plume edge does not exceed any drinking water standard or 1 mg/L GRO or DRO. In addition, assessing potential vertical contaminant migration may be required, but defining the vertical extent of groundwater impacts is not required at this point.

1. **Groundwater sampling**
    - Collect groundwater samples from all soil borings (temporary wells) where groundwater is encountered.
    - Set temporary well screens to intersect the water table. Provide well construction diagrams for each temporary monitoring well. See Section III.B.2 below for well construction diagram requirements.
    - Collect additional groundwater samples below the water table if contamination extends 10 or more feet below the water table.
    - Collect and analyze groundwater samples following the procedures and analytical requirements described in Groundwater Sample Collection and Analysis Procedures.

2. **Aquifer determination**

    Aquifer determination is based primarily on the transmissivity of the impacted hydrogeologic unit. Transmissivity is a function of hydraulic conductivity and saturated unit thickness. Hydrogeologic units with a transmissivity greater than 50 ft^2/day are considered aquifers. In addition, any unit that produces water to a supply well or spring is considered an aquifer, regardless of the estimated transmissivity.

    Hydraulic conductivity: Use an empirical formula to estimate hydraulic conductivity from the grain-size analysis results of samples collected within the saturated zone (Section II.C.2). Select a formula that is applicable to the grain-size analysis results. For example, do not use a formula if a sample's effective grain diameter or coefficient of uniformity does not fall within the formula's applicable range. If no empirical formulas are applicable, use the value listed in Table 4 for the appropriate soil type. If using Table 4, use the soil type designation from the grain-size analysis results, not the in-field soil type designation.

Table 4. Referenced hydraulic conductivity values.[1]

Soil type	Hydraulic conductivity (cm/s)	Hydraulic conductivity (ft/d)
Clay	10^{-6}	0.002835
Silt, sandy silts, clayey sands, till	10^{-4}	0.2835
Silty sands, fine sands	10^{-3}	2.835
Well-sorted sands, glacial outwash	10^{-1}	283.5
Well-sorted gravel	1	2835

[1]Fetter, C.W. 2001. Applied Hydrogeology. 4th ed. Prentice-Hall, Inc., Upper Saddle River, NJ. Values represent the higher end of hydraulic conductivity ranges from Fetter (2001).

Hydrogeologic unit thickness: Determine the saturated unit thickness according to what each grain-size sample represents and soil boring data, nearby well records, or other published information. If the sample represents a single impacted unit, use the saturated thickness of that unit. If the sample represents a thinner, more conductive layer within a thicker, less conductive unit, use the thickness of the more conductive layer. Note, however, that the thicker, less conductive unit may also meet the definition of an aquifer. Thickness is not limited to the vertical extent reached in soil borings if other information indicates the unit extends beyond the maximum drilling depth.

Final aquifer determination: If any grain-size sample's transmissivity is greater than 50 ft^2/day, it is considered an aquifer. Justify the aquifer determination in the Investigation Report by explaining the rationale for the selected grain-size sample locations, hydraulic conductivity estimates, and unit thicknesses.

3. **RI determination**

    An RI is required if the LSI determines one of the following, conditions exist:

    - An aquifer has been (or is likely to be) contaminated by petroleum compounds at concentrations above drinking water standards or above 1 mg/L GRO or DRO.

- Surface water has been (or is likely to be) contaminated by petroleum compounds at concentrations above applicable surface water standards or above 1 mg/L GRO or DRO.
- Mobile LNAPL is encountered.

An RI may be necessary if certain other site-specific conditions are present. If an RI is not necessary, submit the LSI.

B. Remedial investigations

Remedial investigations measure groundwater contaminant concentrations in monitoring wells over time to determine whether a plume is stable. Monitoring well data also are used to calculate travel times within an impacted aquifer to evaluate risk to groundwater receptors. The following section explains monitoring well placement and construction, aquifer characterization, and monitoring well data evaluation.

1. Monitoring well placement

Worst-case monitoring wells: Place monitoring wells within or close to any confirmed or likely source area (e.g., underground storage tank basins, aboveground storage tank areas, product transfer areas, buried lines, pump islands, remote fill pipes, and known spill areas). Install monitoring wells to define mobile LNAPL (if present).

Lateral and downgradient monitoring wells: Place monitoring wells to define plume width and length. Place monitoring wells in an arrangement that defines the downgradient extent of the groundwater contaminant plume (any contamination exceeding drinking water standards or 1 mg/L GRO or DRO). At least one downgradient monitoring well must be located within 20 degrees of the longitudinal axis of the plume. The longitudinal axis is determined using hydraulic gradient measurements. If hydraulic gradient measurements are inconsistent between monitoring events or inconsistent with the plume's geometry, use plume geometry to determine the groundwater flow direction.

Deep monitoring wells: A deep monitoring well has its screen set entirely below the water table. Consideration needs to be given to the design of deep monitoring wells, including screen length and placement. There are several situations when deep monitoring wells may be needed:

- If soil borings show, that contamination has migrated more than 10 feet below the water table.
- If an evaluation of hydrogeologic data indicate downward contaminant migration is likely.
- If the impacted aquifer is a drinking water aquifer, or hydraulically connected to a deeper aquifer, with an active water supply well within 500 feet.

A network of deep monitoring wells may be necessary to determine the three-dimensional extent of the plume, calculate flow direction, and estimate travel time.

Contact the MPCA before installing a deep monitoring well. Be prepared to discuss site stratigraphy, well receptors, and monitoring well construction.

Legal access for off-site monitoring wells: Legal access for off-site monitoring well locations may prove difficult in some locations. If legal access is not obtained after two written attempts, contact the MPCA for assistance.

Screen placement:

- Install water table monitoring wells so the water table intersects the screen. Document and justify any exceptions in the Investigation Report.
- Deep monitoring well screens do not intersect the water table. Screen placement depends on the purpose of the well. If the well is installed to measure vertical gradient, the top of the screen should be at least twenty feet below the water table (but within the same aquifer). If the well is installed to monitor water quality in a deeper aquifer, place the screen entirely within that aquifer, typically using a five-foot screen.

- During monitoring well construction at sites where geologic conditions make it difficult to determine the actual depth to water, allow the borehole to remain open at least 24 hours prior to monitoring well completion to let the water level to stabilize.
- Consider using a slightly longer well screen (15-20 feet) to compensate for water table fluctuations.
- Phased well installation may be appropriate. This allows for determination of the approximate water table depth in one or two wells, and then the remaining wells can be installed with proper screen placement.

2. Monitoring well construction

- Construct monitoring wells in accordance with the Minnesota Department of Health water well construction code. However, it is recommended that monitoring wells not be installed in borings that extend more than 10 feet beyond the bottom of the screen.
- Properly clean all monitoring well materials prior to installation.
- In general, avoid the use of liquid drilling fluids. However, they may be approved by the MPCA on a site-specific basis.
- Properly develop all wells to ensure adequate hydraulic connection with the aquifer and to remove any drilling fluid if used. Document the development procedures and results.

Complete monitoring well construction diagrams for every monitoring well. The minimum information required includes, but is not limited to:

- Diagram of major well features (borehole annulus, top and bottom of screen, casing/riser, top and bottom of sand pack, top and bottom of pack seal, grout, surface seal, protective casing, etc.).
- Depth from ground surface to all major well features including top of casing (feet).
- Well screen slot size (inches).
- Sand pack size (inches).
- Inner diameters of riser casing, screen, protective casing, and borehole (inches).
- Well development information (date, start/end times, methods used, gallons pumped, turbidity, recharge, etc.)
- Well construction materials.
- Unique well number and project identification number.
- Date well begun and completed.
- Driller and consultant names.
- Elevation of ground surface and measurement point, i.e., top of riser casing (feet, relative to identified datum).

3. Aquifer characterization

Aquifer characterization involves calculating groundwater velocity and travel time.

Groundwater velocity: The velocity at which groundwater is moving in the aquifer, or seepage velocity, is calculated using the hydraulic conductivity (K), the hydraulic gradient (dh/dl), and the effective porosity of the aquifer (n_e).

$$v = -\frac{Kdh}{n_e dl}$$

Hydraulic conductivity is determined using grain-size analysis results as described in Section III.A.2 above. Select a hydraulic conductivity that represents the contamination's primary flow path, which will typically be the highest conductivity. Measure the hydraulic gradient in monitoring wells during the RI; use an average gradient when multiple measurements are available. If deep wells are installed, separately measure the hydraulic gradient in the deep well network. Estimate effective porosity using a referenced value based on the aquifer material. Calculate the velocity for the water table aquifer. If deep wells are installed, also calculate the velocity at depth.

Estimated travel time: Using the groundwater velocity described above, calculate the distance groundwater will travel in five years. Evaluate whether a receptor exists within the estimated five-year travel time of the plume edge. If there are no receptors within a five-year travel time, the aquifer characterization is complete for submitting the Investigation Report.

Measured travel time: When a groundwater receptor is within the estimated five-year travel time of the downgradient plume edge, the MPCA may require a more robust travel-time calculation to further evaluate risk. This travel-time calculation is referred to as a measured travel time. One option is to complete a pump test to determine the hydraulic conductivity. In general, a single-well pump test is completed following the standards in Minn. R. 4720.5530. Use the hydraulic conductivity determined from the pump test to recalculate groundwater velocity and travel time. Other options may also be proposed to measure travel time.

Deep monitoring wells: When deep monitoring wells are installed to evaluate vertical contaminant migration, calculate vertical hydraulic gradients for all nested well pairs. Determine groundwater flow direction using the measured hydraulic gradient in the deeper well network and the plume's geometry.

4. Data evaluation

Investigation Report submittal: Submit the Investigation Report after two quarters of groundwater sampling. Continue quarterly sampling from all monitoring wells until site closure or until the MPCA approves a different sampling schedule.

For the Investigation Report, consider the following questions when evaluating monitoring well data.

- Has the plume extent been adequately delineated with monitoring wells?
- Is there an adequate downgradient monitoring well along the longitudinal axis of the plume?
- Is groundwater flow direction certain?
- If mobile LNAPL is present, has it been delineated with monitoring wells?
- Is there a need to evaluate the vertical extent of groundwater contamination?

Post-Investigation Report submittal: In addition to the questions listed above, consider the following questions for monitoring data collected after the Investigation Report:

- Is the groundwater plume stable, expanding, or is stability not apparent?
- Are contaminant concentration trends apparent in all wells? Are the trends consistent or inconsistent between wells?
- Have water levels shown seasonal or other significant fluctuations? Are contaminant concentrations correlated to water level fluctuations?
- Is the monitoring well network still adequate to evaluate plume stability?
- Is there evidence of migrating LNAPL?

Plume stability: Multiply lines of evidence should be used to evaluate plume stability. Creating time series plots to show contaminant concentrations over time is one line of evidence that is useful for visualizing data and qualitatively evaluating trends. Plot water levels on the secondary y-axis to look for correlations between water level and concentration. At least six quarters of groundwater monitoring data are required to complete a qualitative trend analysis.

Another way to evaluate plume stability is by monitoring for natural attenuation. Various natural processes can control the movement of a petroleum plume and act to limit the risks. Additional parameters can be collected during groundwater sampling events in order to assess for natural attenuation. Assessment of natural biodegradation at petroleum release sites is described in https://www.pca.state.mn.us/sites/default/files/c-prp4-03.pdf.

In addition to natural attenuation, natural source zone depletion (NSZD) is a combination of processes that can reduce the mass of LNAPL in the subsurface. These processes include dissolution of LNAPL constituents into groundwater and volatilization of LNAPL constituents into the vadose zone. Additional information on NSZD can be found in the following publication:

ITRC (Interstate Technology & Regulatory Council). 2009. Evaluating Natural Source Zone Depletion at Sites with LNAPL. The Interstate Technology & Regulatory Council LNAPLs Team https://www.itrcweb.org/GuidanceDocuments/LNAPL-1.pdf.

For sites with nearby receptors, expanding plumes, impacts to a drinking water aquifer, or impacts to water supply wells below drinking water standards, groundwater monitoring is likely to extend beyond six quarters. For sites with sensitive groundwater conditions, groundwater monitoring is required for a minimum of three years as described in Guidance Document 4-18 Assessment of Sensitive Groundwater Conditions. When at least 10 sampling events have been completed, a statistical trend analysis such as Mann-Kendall, the Ricker Method, or another approved analysis can be used as another line of evidence to evaluate plume stability. Statistical analyses may have specific data collection and analysis requirements to obtain valid results, so it is important to consider test requirements at the start of the investigation.

Additional information regarding statistical analysis for groundwater monitoring data can be found in the following publication:

ITRC (Interstate Technology & Regulatory Council). 2013. Groundwater Statistics and Monitoring Compliance, Statistical Tools for the Project Life Cycle. GSMC-1. Washington, D.C.: Interstate Technology & Regulatory Council, Groundwater Statistics and Monitoring Compliance Team. http://www.itrcweb.org/gsmc-1/.

Ground Water Monitoring and Remediation. 2008. A Practical Method to Evaluate Ground Water Contaminant Plume Stability by Joseph A. Ricker. Ground Water Monitoring & Remediation 28, no. 4: 85–94.

Other considerations when evaluating groundwater data include:

- Evaluate concentration trends both within the plume and at the plume edge. Are consistent trends seen across the plume, or is there an increasing trend within a part of the plume?
- Data from worst-case monitoring wells may not be suitable for assessing trends if located in areas of residual LNAPL because of the potential for significant concentration fluctuations between sampling events.
- Monitoring wells located beyond the plume edge with non-detectable concentrations should not be used as the only line of evidence to indicate a stable plume.

Before implementing any of these plume stability tools, please contact your MPCA project team to discuss. It is up to the MPCA to determine site closure; therefore, additional work may be requested to reinforce site decisions.