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Groundwater Investigation and Characterization

Introduction

This document provides guidance to qualified professionals for the investigation and characterization of groundwater at sites in British Columbia that may be, or are, contaminated. It is the responsibility of the site owner or operator to retain a qualified professional with demonstrable experience, as required under section 63 of the Contaminated Sites Regulation (the Regulation), to ensure that groundwater is properly characterized and remediated while adhering to applicable B.C. laws, regulations, standards, protocols, procedures and guidance.

This guidance is based on the ministry's full length companion document entitled "Technical Guidance for Contaminated Sites. Groundwater Investigation in Site Assessment, 2nd Edition", dated June 17, 2010 [1]. Both this guidance document and the companion document should be used as part of any contaminated site groundwater investigation.

The guidance and procedures outlined here are not applicable at every site; others may also be used. However, deviations from this guidance or use of alternative methods must be accompanied by documented, defensible rationale.

When is groundwater investigation necessary?

Site investigation stages

The Regulation contains requirements to ensure that groundwater at a site or on a neighboring site is suitable for use and is of adequate quality to protect uses now and in future. Where site investigations must be undertaken, section 58 (1) of the Regulation requires that a preliminary site investigation (PSI) be undertaken to determine the general location and degree of contamination, including any migration that may have occurred to neighbouring properties.

The PSI comprises a Stage 1 review and a concurrent or subsequent Stage 2 where relevant environmental media are sampled for potential contaminants of concern (PCOCs). If contamination is identified or suspected then a detailed site investigation (DSI) must be undertaken in accordance with section 59 (2) of the Regulation to define the extent of contamination, to provide information necessary for conducting a risk assessment, if applicable, and to develop a remediation plan.

Groundwater investigation triggers

Groundwater investigation is necessary if the potential exists for the quality of groundwater to be unsuitable for direct use, based on groundwater uses at the site, or may not be adequate to protect adjacent groundwater uses.

Groundwater investigation is also necessary where groundwater is acting as a source of contamination in other environmental media such as vapour. In practice, where areas of potential environmental concern (APECs) are identified by a Stage 1 PSI, relevant environmental media must include groundwater, which should be sampled as part of the subsequent Stage 2 PSI and/or DSI. If groundwater is not sampled, detailed supporting rationale for its exclusion must be provided in the PSI or DSI report.

What are B.C.'s groundwater quality classes?

Based on its use, the Regulation provides four classes for groundwater:

DW – drinking water
AW – aquatic life protection
IW – irrigation water
LW – livestock watering

Aquatic life protection standards are further subdivided into standards to protect freshwater aquatic life and standards to protect marine and estuarine aquatic life.

Numerical standards for many potential contaminants in water are listed in Schedule 3.2 of the Regulation. Monitoring results may be compared directly to the substance concentrations in these schedules to determine whether a groundwater source is in compliance with applicable water use standards. Guidance for selecting water uses is provided in Protocol 21, "Water Use Determination".

How should a field program be designed?

A well-designed field program will yield a data set composed of representative physical and chemical information on soil, vapour, sediment, groundwater and surface water conditions obtained from a number of locations and depths at various times. It is important that applicable groundwater standards are compared to accurate and reliable groundwater quality data that represent, to the greatest extent practical, the quality of the groundwater at a site.

The conceptual site model

For effective planning of any site investigation, the historical, physical, chemical and biological components that define a problem should be drawn together into a conceptual site model (CSM). In a hydrogeological context, the CSM should comprise a three-dimensional understanding of the site to be investigated. The CSM should be developed at the outset of the investigative process and refined throughout the course of the investigations to strengthen and clarify the site understanding. At the completion of investigations, the CSM should, as a minimum, include key hydrogeologic features and properties such as:

- the physical geologic setting including the known or inferred extent and continuity of all aquifers and aquitards that are beneath and in the vicinity of the site that are or may be of relevance;
- groundwater levels (pressure heads, water-table elevations, potentiometric surfaces) and hydraulic gradients (vertical and horizontal) within and between relevant permeable geologic units;
- the physical and hydrogeologic boundaries that define the groundwater flow systems of interest, including recharge and discharge areas, pumping wells, hydraulic and physical no-flow boundaries or divides, and other relevant conditions;
- the locations and character of onsite and relevant offsite potential source zones of contamination to groundwater, including any nonaqueous phase liquids (NAPL) if present, and their composition, nature, and extent;
- the locations, extent and character of associated dissolved-phase plumes of

contamination that may exist; and

- all pathways for contaminant transport from source zones to known or potential receptors, including pathways that may convey nonaqueous phase, dissolved-phase or vapour-phase plumes that may be expected to develop in the future.

The CSM must be supported with a data set derived from sound investigative practices, as provided in this and other guidance documents, and any pre-existing information or data that have been identified and can be relied upon. Supporting rationale should be provided for such data. Depending on the level of site complexity, the CSM may be portrayed together with descriptive text in a set of plan maps and stratigraphic cross sections or fence diagrams. As part of the CSM, key processes that may significantly influence the presence, distribution and fate of potential contaminants of concern at a site (e.g., advection, dispersion, retardation, ion exchange, precipitation, dissolution, diffusion, volatilization and biodegradation) should be identified and described where available data make such assessments possible.

What methods and approaches are acceptable for groundwater field investigations?

A range of direct and indirect approaches is available to acquire information on groundwater quality (e.g., CCME's guidance manual for environmental site characterization [2] and Attachment B of the companion document to this guidance [1]), any of which may be acceptable for use in B.C. However, it is critical that the field investigation include the acquisition and analysis of representative groundwater samples.

Obtaining groundwater quality information

Conventional monitoring wells that are properly installed and sampled provide an acceptable means to acquire representative groundwater samples for Stage 2 PSIs and DSIs. Such wells are commonly composed of a riser pipe inserted into a drilled borehole, with a screened completion interval at the base that is placed within a targeted geologic unit. A recommended design for conventional monitoring wells is provided in the "British Columbia Field Sampling Manual".

> The use of drill cuttings as backfill is to be avoided. Recommended sealants along the well annulus include non-shrinking bentonite-based grouts or solids. In cases where granular bentonite, bentonite chips, or bentonite pellets are used, proper hydration of the bentonite during placement should be ensured, particularly if the sealing material is located in the unsaturated zone. Any deviation from these requirements should be identified in site investigation reports, together with supporting rationale.

In addition to the design, installation and sampling of a network of conventional monitoring wells, a variety of screening-level approaches and multi-depth tools are available that can be used during the PSI and DSI to complement groundwater data and identify the presence, absence or extent of groundwater contamination. These range from simple descriptive observations of continuous cores of soil or rock, to direct-push profiling tools such as laser-induced fluorescence tools, the membrane interface probe, or the Waterloo Profiler™. These approaches may be used to complement data obtained using conventional monitoring wells.

Vertical contaminant distribution

In aquifers where groundwater contamination may exceed one to two metres in thickness, groundwater quality profiles should be defined using clusters or nests of wells completed at different depths, or by using other groundwater profiling technologies. Alternative approaches to conventional monitoring wells include various tools and technologies that can be demonstrated to yield reliable quantitative or semi-quantitative information on groundwater quality either directly (e.g., direct-push groundwater sampling technologies such as the Waterloo Profiler™), or indirectly through acquisition of soil quality profiles *in situ* (e.g., using technologies such as laser-induced fluorescence or a membrane interface probe) or *ex situ* (e.g., analysis of discrete soil samples or extracted fluid samples from soil cores).

Obtaining hydrogeologic information

Hydrogeologic information should be acquired through drilling, well installation, and well monitoring and testing programs, or through alternative approaches that yield comparable site-specific data. Soil and/or rock core samples are usually obtained and used to describe physical aquifer conditions, and hydraulic tests or measurements are made to acquire hydraulic information about the aquifer. Field tests may range from simple static water-level measurements that can be used to assess the water table or piezometric surface of the aquifer, to more involved aquifer pumping tests that hydraulically stress a region of the aquifer, and thereby allow estimation of local and/or regional-scale hydraulic parameters (e.g., hydraulic conductivity, transmissivity, specific yield, storativity).

Well development, purging and sampling

A description of well development, purging and sampling methods to be used in the investigation of groundwater conditions and quality at contaminated sites is provided in Attachment A of the companion document [1].

Acceptable lengths of monitoring well screens

Maximum saturated screen lengths should be limited to 1.8 m (i.e. screen plus filter pack) within the target hydrostratigraphic unit. Preference should be given to smaller intervals so that maximum concentrations are better defined. Rationale must be provided where longer well screen lengths with greater saturated thicknesses are used.

Where a water table aquifer is monitored, the screen length should not extend beyond a depth of one metre below the greatest depth to the water table as defined by the seasonal minimum and/or minimum groundwater elevation during low tide.

The use of wells with long screen intervals may be acceptable for exploratory purposes during a Stage 2 PSI (but not a DSI) provided that cross communication between potentially separate groundwater zones is avoided. However, where saturated well screen intervals exceed 1.8 m, chemical data for samples from such wells should not be compared directly with groundwater quality standards unless supporting rationale can be provided.

Wells that are no longer being used or that are inadvertently screened across more than one aquifer should be decommissioned promptly (i.e., at or before the completion of a site investigation), to avoid risk of future cross contamination.

What level of groundwater investigation is required for a preliminary site investigation?

Stage 1 preliminary site investigation

Groundwater investigation should begin during Stage 1 of a PSI and should include attempts to acquire geological, hydrostratigraphic and groundwater use information about the site and vicinity (refer to Technical Guidance 10, "Guidance for a Stage 1 Preliminary Site Investigation"). If APECs are identified, then the assembled information should be evaluated to assess the potential for contamination of the environmental media, including groundwater. To assist with this evaluation, a CSM should be developed with a hydrogeologic focus. It will also serve as a basis for planning the next phase of the field investigation, the Stage 2 PSI.

Stage 2 preliminary site investigation

The type and scale of investigation selected and implemented during a Stage 2 PSI, and the media to be sampled, will be highly dependent on local site conditions and on characteristics of the potential contaminants of concern (PCOC). The success of the program will depend on the degree of understanding of these conditions as described by the CSM. A well-developed CSM is likely to better achieve Stage 2 PSI objectives than a program based on limited information that has not been cohesively assembled within a logical framework. Where site-specific information is lacking but groundwater quality is to be addressed, a Stage 2 PSI could consider the drilling and logging of a "stratigraphic" borehole, located beyond all zones of potential contamination, to establish site-specific stratigraphic conditions and to identify target intervals for further testing (e.g., water table, saturated geologic units, and aquifers).

During the Stage 2 PSI, monitoring well locations should be selected to intercept highest concentrations of potential contaminants in groundwater associated with each suspected source zone within each on-site APEC, and at the property boundary as close as practical to off-site APECs. If underground utility corridors exist, a review of the utility location maps and depth information is required to assess the presence of preferential pathways near APECs and aid in determination of well locations.

Groundwater flow direction should be established as part of the Stage 2 PSI and used to re-assess the optimum sampling locations with respect to anticipated highest concentrations. Groundwater flow direction should be estimated using water-level measurements acquired from a minimum of three locations arranged in a triangular plane within the same hydrogeologic unit (i.e., the same aquifer). Caution is advised, however, where groundwater flow patterns are complex. Data from more than three wells will likely be necessary to resolve flow directions where, for example, groundwater mounding results in radial flow, where diving or sinking plumes are present, and where unforeseen high-permeability features such as buried gravel channels or utilities are present.

At the completion of the Stage 2 PSI, information should be presented and conclusions drawn regarding the presence or absence of groundwater contamination associated with each APEC. In addition, confirmation of the groundwater flow hypotheses that were used to base the inclusion and exclusion of potential APECs during the Stage 1 PSI should be conducted. Where the groundwater flow information determined during the Stage 2 PSI differs from that inferred in the Stage 1 PSI, the Stage 1 PSI conclusions with respect to APEC selection should be re-examined. The CSM should also be updated.

If groundwater is identified as contaminated, then recommendations for further assessment in the form of a DSI should be provided.

Conditions requiring further investigation

Further assessment in the form of an expanded Stage 2 PSI or DSI should be conducted where:

- groundwater is identified as contaminated, or,
- a well or set of wells is determined to have missed the highest concentrations of a possible plume because the well(s) is not located directly downgradient of the potential source zone.

Further assessment should also be considered where PCOCs have been detected in groundwater and the water quality data are limited to a few data points.

What level of groundwater investigation is required for a detailed site investigation?

As required in section 59 (2) of the Regulation, a DSI must, among other items, include procedures to identify the specific areas, depths and degree of contamination on the site, including areas and extent of migration if applicable, and evaluate contamination relative to standards in the Regulation. For purposes of this guidance, and except where a Stage 2 PSI report has concluded that groundwater is not contaminated, groundwater assessment must be undertaken during the DSI. The sampling program must be sufficiently detailed to satisfy data requirements for a risk assessment, if applicable, and for developing a remediation plan.

Well spacing and spatial characterization

For groundwater investigation during a DSI, the following guidance is provided to ensure that plumes of contamination are identified and characterized with reasonable certainty. An example of acceptable well spacing intervals and well completion depths for a groundwater plume is illustrated in Appendix 1, Figure 1. As each site is unique, variations from this guidance are to be expected. However, any deviation from the requirements presented below must be identified, together with supporting rationale and consequent implications on the uncertainty of the acquired data set.

The site assessment should characterize substance concentrations with reasonable certainty so that:

- all groundwater plumes of significant size (typically 10 m or longer longitudinally, 5 m or wider laterally, and 0.1 m or thicker vertically) are identified with reasonable certainty such that the horizontal and vertical boundaries are resolved at the scale identified in Appendix 1, Figure 1; and
- the effects of well screen length and dilution at the location of a potential receptor are understood and taken into account in the investigation.

Vertical separation between wells

Where a groundwater plume is confirmed or suspected, it should be resolved to a vertical scale that is compatible with the scale of the stratigraphic layering that is likely present.

In the absence of site-specific rationale, data to define and bound the vertical extent of a plume should be derived from locations that are separated vertically by no more than one metre from the bottom of one well or sampling point and the top of the next, within each aquifer of interest (Appendix 1, Figure 1). Where monitoring wells are used, care must be taken to select a small enough screened interval to avoid cross-communication between aquifers, or even between significant stratigraphic layers within the same aquifer.

Chemical characterization

The detailed site investigation should include the chemical analysis of representative samples for appropriate substances and parameters at the appropriate detection limits.

The suite of substances selected for a site investigation should include the following:

- contaminants of known or potential concern, modifying factors (pH or hardness) that are used to establish the applicable standard for certain contaminants, and the potential transformation products in the subsurface that may pose risks to receptors.

In addition, the substance suite may also include the following:

- inorganic constituents (more commonly major ions, and less commonly dissolved gases and/or isotopes) that may assist in addressing the hydrogeologic characterization, and

- geochemical and chemical information that will assist in assessing contaminant transport and fate in the subsurface (e.g., redox conditions, soil and dissolved organic carbon content, dissolved oxygen and pH, nutrients, hardness, etc.) during migration through the aquifer to a receptor.

Temporal characterization

Several factors may account for observed changes in substance concentrations over time, including changing water levels caused, for example, by changes in seasonal infiltration rates or tides, and changes resulting from biotransformation or source depletion.

The site investigation should obtain a sufficient number of samples to establish the magnitude of temporal concentration variations or to allow predictions to be made with reasonable certainty. Where seasonal effects may be significant, or where concentrations are likely to vary significantly for other reasons, then at least quarterly sampling should be performed over at least one year.

Preferential transport pathways

All site investigations should address the possibility of contaminant transport along preferential pathways such as utility corridors and drainage improvements. This will involve a review of utility location maps and depth information, which can then be compared with known information concerning the site stratigraphy, water table elevations, and presence and extent of contamination.

Plume Stability Assessment

The demonstration of stable or decreasing contaminant plumes must include the evaluation of groundwater conditions within and at the margins of contaminant plumes and provide evidence of both stable or decreasing substance concentrations throughout and no additional vertical or lateral migration or rebound effects. A minimum of two years of groundwater monitoring and geochemical data (including seasonal variations over a two-year period) demonstrating stable or decreasing groundwater concentrations and conditions is expected to be collected.

In some cases (e.g., sites with long term monitoring data or monitoring coupled with remediation efforts), other means of evaluation/lines of evidence could be used to demonstrate plume stability as follows:

- A minimum of one year of quarterly groundwater monitoring and geochemical data (including assessing groundwater conditions over the range of seasonal/temporal variations), coupled with other methods of evaluation/lines of evidence that in sum demonstrate plume stability (e.g., partial/complete source removal, conservative modelling, etc.).

Trend analysis (e.g., Mann-Kendall test, $\alpha=0.05$) of the monitoring data used to support the demonstration of stable or decreasing concentrations within and at the margins of the contaminant plume is required as part of assessment of plume stability.

The plume stability assessment must be carried out by a qualified professional with demonstrable experience in (a) assessment of groundwater flow, contaminant fate and transport, and aqueous geochemistry, and (b) trend analysis.

Hydrogeologic information

Defining site-specific hydrogeologic conditions

In addition to defining the presence, distribution and fate of the contaminants, groundwater investigations during a DSI should also define site-specific hydrogeologic conditions including:

- the presence, extent and properties of aquifers and aquitards underlying the site that are or may be of relevance;
- zones of high hydraulic conductivity that may act as preferential transport pathways, and zones of low conductivity that may impede or redirect transport;

- unconfined and confined aquifers;
- vertical and lateral hydraulic gradients, groundwater flow direction and velocities within and between the relevant, permeable geologic units;
- physical and hydrogeologic boundaries that define the groundwater flow systems of interest, including recharge and discharge areas, pumping wells, hydraulic or physical no flow boundaries or divides, and other relevant conditions; and
- event and seasonal contributions to the hydrogeologic regime as well as tidal influence (where appropriate), with a focus on identifying conditions required for sampling to be conducted such that it is characterizing as close to the "worst case" scenario as reasonably possible.

The investigation of groundwater flow direction and velocity should, at a minimum, include the following:

- all wells should be surveyed with reference to an elevation datum (a geodetic datum is preferred, although a site-specific reference datum is acceptable),
- static water levels should be measured on the same day from monitoring wells at several locations within the same aquifer, and,
- the groundwater elevation data should be calculated and tabulated.

Entry of information into drawings

Groundwater elevation data should be posted on drawings and, where sufficient data are available, contoured in plan view for each aquifer of interest. Potentiometric surfaces should be shown for each aquifer on each stratigraphic cross section. The flow direction in each aquifer should then be estimated with respect to the data and data contours, and shown on the drawings.

Erroneous measurements

Outliers

Where the data allow, contouring should be conducted within the context of the CSM, with particular attention paid to "outliers" that may become apparent during contouring. Potential or probable causes for the outliers should be described. Some common causes for outliers include, for example, data acquired from wells completed with long well screens and/or at different depths within the aquifer, where vertical hydraulic gradients are present within the aquifer, or where wells are installed across more than one aquifer or groundwater flow zone. These types of well completions are not encouraged as they may yield non-representative water-level data and also may allow flow between zones and serve as conduits allowing contaminant migration between the zones.

Light Nonaqueous Phase Liquids **(***LNAPL)*

The presence of LNAPL in a well may also yield erroneous measurements of water elevation. Where significant floating NAPL is present (i.e., greater than a few centimetres), information on LNAPL thickness must be factored in to determine the actual groundwater elevation, to account for the density difference between the LNAPL and groundwater.

Short-term changes

Estimates of groundwater flow direction may also be influenced by short-term changes in water elevation or hydrostatic pressures in confined or unconfined aquifers caused, for example, by tidal fluctuations or changes in river stage during spring freshet. In such cases, water levels in an aquifer should not be considered static, and one or two simple "snapshot" measurements of water levels in wells from a site are unlikely to yield reliable data for estimating average groundwater flow direction or velocity.

Where multiple hand measurements of water levels cannot be readily obtained from site monitoring wells over a full tidal cycle (i.e., at sites with more than three or four monitoring wells) water-level data should be acquired from individual wells using automatic measurement devices such as pressure transducers. The time-step interval between measurements and monitoring duration should be commensurate with the expected rate of change of water level. For most tidal conditions, measurement frequencies should be once per hour, over periods of at least 71 hours. In most cases, data reduction and interpretation will require smoothing to establish mean or average conditions over the monitoring period. Where tidal influence is present, the method of Serfes, 1991 [3] is recommended to yield estimates of mean water levels at individual monitoring points. However, in a complex hydrogeologic setting (e.g., highly variable fill soil and/or preferential flow channels) examination of the pressure transducer data at specific points in time may also be of value in describing the groundwater flow system.

In cases where the site is located in proximity to a marine environment, saltwater intrusion is very probable. Accordingly, deeper wells may be screened within a saltwater wedge, whereas shallower wells may be screened within freshwater. Water-level data obtained from wells screened within saltwater must be corrected for density contrasts and converted to equivalent freshwater head. This conversion is critical to properly evaluate vertical and horizontal hydraulic gradients, and to accurately characterize groundwater flow when constructing potentiometric surface maps.

When should nonaqueous phase liquids be investigated?

The presence of NAPL should be monitored during drilling, well installation and well development. The presence and thickness of any immiscible layers in a well should be established prior to purging and sampling using a reliable technique such as an interface probe. In those wells with NAPL, groundwater sampling is not advisable since measured concentrations may often be lower than actual dissolved concentrations due to sample dilution, or higher than actual concentrations due to entrainment of NAPL in the samples.

Characterization of the NAPL is usually best achieved by direct sampling and analysis, although assessment of dissolved-phase constituents can often be used successfully to infer NAPL composition. NAPL sampling involves the careful use of special bailers or pumps. Acceptable monitoring approaches are described by API, 1996 [4].

LNAPL monitoring

Where subsurface contamination by LNAPL is suspected, monitoring wells should be designed so that the well screen interval straddles the water table, thereby allowing LNAPL, if present, to enter the well. If the well may be used for long-term monitoring purposes, then the well screen length should be selected to straddle the water table over the anticipated seasonal high and low water-table conditions.

Where LNAPL is present, at least one LNAPL monitoring well should be placed within each zone where LNAPL is inferred to be thickest. The lateral boundary of the LNAPL zone should be resolved at a scale of 5 m to 7 m or less, depending on proximity of LNAPL to property boundaries, structures and other sensitive site features. Data to define the boundary may be acquired using various technologies such as monitoring wells, laser-induced fluorescence, soil cores or test pits. However, some LNAPL monitoring wells should be installed in downgradient locations along the perimeter of the LNAPL zone to monitor LNAPL thickness and the possibility of LNAPL migration.

Following well development, LNAPL may not enter the well immediately. Therefore, the well should be allowed to rest at least 24 hours and preferably at least one week before confirming the presence or absence of LNAPL. Where LNAPL is present, a regular monitoring program should be established for at least 12 months (or as long as necessary to assess NAPL migration) or until remediation has been undertaken or LNAPL is demonstrated to be immobile under the criteria specified in Section 3.2 of Protocol 16, "Determining the presence of and Mobility of Nonaqueous Phase Liquids and Odorous Substances". In absence of site-specific rationale, the monitoring frequency at each LNAPL well should be at least once every two months and preferably monthly until the temporal variability and mobility of LNAPL has been established, for the following:

- Total organic vapour concentrations at the well head using a photoionization detector or similar field instrument.
- Water and product levels using a reliable method such as an interface probe.

Based on the results of this investigative phase of monitoring, the monitoring frequency can be reduced to quarterly if warranted.

Groundwater concentrations from wells located downgradient of the LNAPL plume should be analyzed to evaluate potential LNAPL movement. A temporal increase in dissolved concentrations downgradient of the plume may be indicative of LNAPL advancement; conversely, a temporal decrease in dissolved concentrations may be indicative of LNAPL plume retreat.

At tidally influenced sites, monitoring should be conducted over a full tidal cycle at least once to establish the influence of tides on LNAPL presence and thickness.

During the monitoring period and until a well is decommissioned, its integrity should be checked and maintained, including maintaining effective well plugs and seals to prevent cross-contamination.

Dense nonaqueous phase liquid (DNAPL) monitoring

Where subsurface contamination by DNAPL is suspected, care should be taken to avoid drilling through the DNAPL, which may cause the contamination to migrate deeper into the subsurface. DNAPL distributions in the subsurface are often highly complex, and as a result, direct evidence of DNAPL is rarely obtained using conventional drilling and sampling techniques. Thus, a precautionary approach to investigation of DNAPL zones is advised, and alternative investigation approaches should be considered to assess the extent of contamination. These may include using multi-depth sampling at locations immediately downgradient of the DNAPL zone and obtaining soil vapour and shallow soil data mainly from the surface of the zone. Using these indirect approaches, the outer horizontal boundary of the suspect DNAPL zone should be inferred to a reasonably small scale (5 m to 7 m, where practical), depending on proximity of DNAPL to property boundaries, structures and other sensitive site features. The vertical extent of the suspect DNAPL zone should be resolved to a depth interval of 1 m to 2 m. For further information on DNAPL assessment, please refer to Pankow and Cherry (1996) [5] and USEPA (2004) [6].

What types of information should be reported?

Groundwater investigation reports should include a description of the methodology used to evaluate site hydrogeology and hydrogeochemistry and the rationale for the methods used. Summaries of key information should be provided in tables and on figures as a means to convey relevant information. A checklist for data information requirements is provided in Appendix 1.

What degree of groundwater investigation is required for confirmation of remediation?

Where groundwater is to be remediated, remediation planning must consider where and how monitoring will be conducted and how the data will be used to confirm that the remediation objectives have been achieved.

Confirmatory sampling and monitoring

Confirmatory sampling and monitoring locations should be established taking into consideration a number of factors including:

- the known extent of contamination;
- the groundwater flow direction before remediation;
- the possibility and duration of short-term changes in groundwater levels resulting from the remediation (e.g., temporary low water levels following remediation);
- where active groundwater controls are required, changes in groundwater flow are long-term and result in new steady state conditions which need to be confirmed;
- transitioning periods in water levels or groundwater chemistry until long-term or steady-state conditions are re-established;
- expected transport velocities and travel times between remediated areas and monitoring locations; and
- changes in geochemical conditions such as redox potential that may affect the solubility or mobility of some constituents.

Post remediation monitoring locations should be selected to include locations that will intercept each of the zones most likely to contain highest concentrations of the contaminants. Note that remediation wells (e.g. extraction or injection wells) should not be used for evaluation of post-remediation groundwater quality.

Substances to be monitored

Groundwater should be monitored for contaminants of concern as well as transformation products and constituents that may have been mobilized by the remediation (e.g., metals dissolution in response to low redox conditions caused by enhanced *in situ* biodegradation of petroleum hydrocarbons).

Monitoring frequency

Where trends are to be established, the frequency of monitoring should be based upon known hydrogeologic conditions, including estimated groundwater and contaminant transport times, and data requirements.

Minimum requirements

A remediation monitoring program will be different for every site. However, the following items are minimum requirements to confirm groundwater remediation:

- A monitoring network should be established that includes a minimum of three monitoring locations within each affected aquifer associated with each area of groundwater contamination.
- Each groundwater monitoring station (usually a monitoring well, but alternative technologies may be equally effective) from the designated network should be strategically located within the remediation zone or along its immediate perimeter, within the relevant permeable geologic units. Installation by placement of post-remediation monitoring wells during excavation backfilling is to be avoided.
- Groundwater levels and groundwater quality indicator parameters (i.e., temperature, electrical conductivity, pH, redox potential, dissolved oxygen, and

turbidity) should be monitored before each sampling event to verify that static conditions have been attained. As a minimum subset, pH, electrical conductivity plus one additional parameter should be monitored until they have stabilized.

- Once static conditions have been attained, at least two sets of groundwater samples should be collected on different days, at least 24 hours apart, but preferably greater than two weeks apart, where practical. At sites where seasonal effects may be significant, at least two sets of groundwater samples should be collected to capture the full range of seasonal variations.
- Representative samples should be analysed from all designated locations or wells for the contaminants of concern and for possible contaminants that may have resulted as a direct or indirect consequence of the remediation.

When is post remediation groundwater monitoring considered complete?

Post remediation groundwater monitoring may be considered complete when substance concentrations are less than applicable standards, concentrations can be shown to be stable or decreasing, and where rebound can be discounted.

When is long term groundwater monitoring necessary?

With many sites where remediation is undertaken, groundwater quality may not improve immediately, or improvements may not immediately meet applicable standards. In such cases, long term monitoring will be necessary either to establish trends towards meeting the remediation objectives or to provide sufficient data to demonstrate that the standards are met over time regardless of changes in water levels or groundwater flow direction. Statistical approaches may be useful to establish trends in concentration, periodicity, and long term average or mean concentrations at individual well locations.

When and how should monitoring wells be deactivated or closed?

Monitoring wells that no longer serve their intended purpose, such as wells that may remain at the completion of a site investigation or remedial monitoring program, should be properly deactivated and closed. Minimum requirements for well deactivation and closure are provided in section 56 of the *Water Sustainability Act* [7] and in section 9 and Appendix A (Code of Practice for Construction, Testing, Maintenance, Alteration and Closure of Wells in British Columbia) of the Ground Water Protection Regulation [8].

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For more information, please direct enquiries to *site@gov.bc.ca*

Revision history

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July 2010	February 1, 2011	1.0	
August 2017	November 1, 2017	2.0	Updated for CSR Stage 10/11 amendments
December 2020	January 5, 2021	3.0	Included plume stability expectations

Appendix 1.

Guidance for Data Presentation

Borehole and Well Construction Logs

Logs should be provided for all geotechnical wells, boreholes, and all wells and piezometers, presenting complete technical records of conditions encountered, scaled to depths of at least 0.1 m. Logs should contain, at a minimum:

- Site name and location
- Name of driller and onsite professional
- Borehole number and location coordinates
- Start date, completion date, date abandoned or completed as monitoring well
- Borehole depth
- Ground surface elevation, top of casing elevation (for wells)
- Sample type, depth and depth interval for all *in situ* samples
- Sample condition, percent recovery, and other field data (e.g., blow counts, moisture content)
- Materials classification (based on field and laboratory descriptions using the unified soil classification system (USCS; ASTM D2487 and/or ASTM D2488) or equivalent
- Observations including colour, stains, odours
- Drilling observations such as loss of circulation, heaving sands
- Volume and quality of water added during drilling
- Depth to water following drilling
- Water level and date following well completion

Raw data from *in situ* hydraulic tests and copies of laboratory analytical certificates should be provided.

Tables

Tables should be provided that include, at a minimum summaries of all field and laboratory data acquired from current and previous investigations, including:

- Water level depths and elevations along with screened interval elevations; and
- Analytical chemistry results for each environmental medium compared with relevant environmental quality standards

Figures and Drawings

Figures and drawings should include, at a minimum:

- A scaled regional location plan and site plan, showing relevant hydrological, topographical and physiographic features
- A plan of posted data at measurement locations, and contours, where sufficient data are available, of piezometric heads in each aquifer of interest
- Stratigraphic cross sections that are longitudinal and transverse with respect to the known or estimated groundwater flow direction, and that include physical conditions (e.g., stratigraphy, water table, piezometric surface elevations), location and depth of all boreholes, monitoring wells and well screen intervals falling on or near the section, and vertical and horizontal scales
- Posted data at measurement locations, and contours where sufficient data are available, in plan and cross section views, of substance concentrations that show the specific lateral and vertical distribution of either each contaminant of concern or a representative set of contaminants of concern in onsite and offsite soil and groundwater
- Sample locations (with corresponding analytical results used to develop each figure) that are shown on the figure and in tabular form with reference to applicable standards.

Other

- Field sampling sheets should be provided documenting information such as volume of water purged, observations during purging, and relevant field-measured parameters (e.g. electrical conductivity, temperature, pH, dissolved oxygen, redox potential, etc.)

The Contaminated Sites Services Application form, Part E, provides further instructions on key information requirements to be provided on figures where applications for contaminated sites services are to be made for detailed review by Ministry of Environment staff.

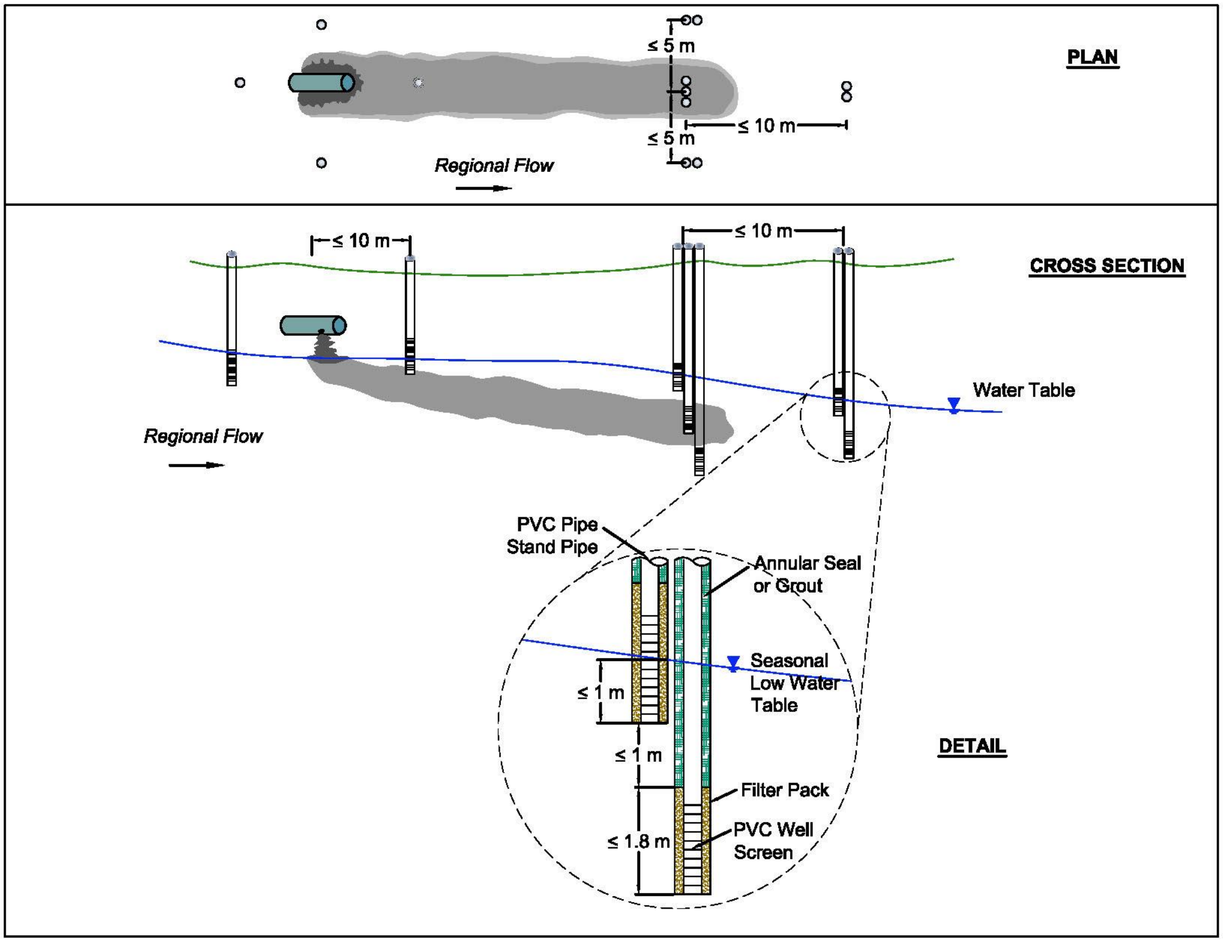

Figure 1. **Example illustrating acceptable well spacing intervals and well completion depths to define the vertical and lateral extent of a plume of groundwater contamination.**

Note. The number of wells used to define the internal plume size and the spacing between these wells may vary from site to site.