Guidelines for Environmental Monitoring at Municipal Solid Waste Landfills

Section 1: Definitions

"adjacent property" refers to a property near a landfill that might be impacted by the landfill's presence and operation (e.g. litter, landfill gas or leachate migration, etc.)**.**

"annular space" means the space between the borehole wall and the well casing, or the spacing between a casing pipe and a liner pipe.

"aquifer" includes any soil or rock formation that has sufficient porosity and water yielding ability to permit the extraction or injection of water at reasonably useful rates.

"attenuation" a process whereby contaminants generated in a landfill are managed, removed or reduced in concentration. Attenuation involves the processes of dilution, filtration, chemical reaction and transformation and may be accomplished naturally under certain conditions.

"contaminant" means a chemical compound, element, or physical/biological parameter, resulting from human activity, or found at elevated concentrations, that may have harmful effects on human health or the environment.

"groundwater" means water below the ground surface in a zone of saturation.

"hydraulic gradient" means the change in static head per unit of distance in a given direction.

"infiltration" is the entry into soil or solid waste of water at the soil or solid waste surface.

"in-situ testing" means testing in the field of materials or naturally occurring substances in their original state.

"landfill gas" is gas produced by the anaerobic decomposition of solid wastes, and includes primarily methane and carbon dioxide, with lesser amounts of other gasses such as hydrogen, hydrogen sulphide, and numerous volatile organic compounds.

"leachate" means any liquid and suspended materials which it contains, which has percolated through or drained from a municipal solid waste disposal facility.

"leachate plume" means contaminated groundwater or soil, beyond the limits of the deposited waste which has been contaminated by leachate from the landfill site.

"lower explosive limit" means the minimum percent concentration (by volume) of a substance in air that will explode or produce a flash of fire when an ignition source is present, measured at 25 degrees Celsius and atmospheric pressure.

"monitoring well" is a water well used to monitor groundwater and occasionally gaseous conditions in the vicinity of a landfill.

"NMOCs" are non-methane organic compounds, primarily composed of VOCs, which contribute to ground level ozone formation. Also known as non-methane hydrocarbons.

"piezometer" is a small diameter, non-pumping well that measures hydraulic and aquifer characteristics such as hydraulic head pressure and compressibility. Piezometers can also be used for groundwater sampling.

"purging" means the removal of stagnant water from a monitoring well casing.

"static head" means the distance from a standard datum of the surface of a column of water that can be supported by the static pressure at a given point.

"surface water" means lakes, bays, sounds, ponds, impounding reservoirs, perennial or ephemeral streams and springs, rivers, creeks, estuaries, marshes, inlets, canals, the Pacific Ocean within the territorial limits of British Columbia, and all other perennial or ephemeral bodies of water, natural or artificial, inland or coastal, fresh or salt, public or private, but excludes groundwater or leachate collection channels or works.

"vadose zone" means a subsurface zone above the water table in which the interstices of a porous medium are only partially filled with water.

"VOCs" are volatile organic compounds, which participate in atmospheric photochemical reactions, related to the generation of ground level ozone. VOCs are a subset of NMOCs.

"well development" means the restoration of natural hydraulic conditions in a monitoring well after drilling accomplished by removing any silt or sand sized particles from the filter pack and surrounding formation.

"well nest" means a closely spaced group of wells screened at different depths, whereas a multi-level well is a single device with two or more monitors sealed at different depths.

Section 2: Introduction

These guidelines are intended to assist landfill owners and operators to design and implement an environmental monitoring program as required by section 7.15 of the **Landfill Criteria for Municipal Solid Waste**. Effective monitoring programs will enable landfill operators to demonstrate that they meet the performance criteria contained in section 4 of the **Landfill Criteria for Municipal Solid Waste**, and most importantly, will help prevent unacceptable environmental impacts throughout the lifespan of the landfill.

Monitoring programs should include regular evaluations of groundwater, surface water, leachate, landfill gas, and ambient air quality as dictated by the nature of the facility on a case by case basis. Additional parameters, such as soils or vegetation, should be monitored where a risk is assessed as indicated in the landfill criteria (BC Environment, June 1993).

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Section 3.0: Groundwater Monitoring

Groundwater monitoring at landfills is meant to detect unacceptable groundwater contamination resulting from landfill operations. Acceptable contaminant levels are specified by the Manager and will generally be in accordance with the **Approved and Working Criteria for Water Quality — 1995** , published by the Water Quality Branch of the British Columbia Ministry of Environment, Lands, and Parks.

The location and number of wells required to adequately describe hydrogeological conditions will depend upon the site-specific geology, soil and groundwater regime. Networks of wells are often developed in phases, with data reviewed at the end of each phase to determine if the hydraulics of the site are being adequately defined. A groundwater monitoring well network should consist of a sufficient number of wells, installed at appropriate locations and depths, to yield samples that represent the quality of both ambient groundwater and leachate which has passed under or through the disposal area of the landfill (Environmental Protection Agency (EPA), 1993).

Groundwater monitoring programs should be designed and carried out by qualified personnel to ensure consistent representative sampling. All monitoring and sampling equipment must be operated and maintained to perform to design specifications for the duration of the monitoring program.

Since the monitoring program is intended to operate through the entire post-closure period (a minimum period of 25 years) as well as the operational period of the landfill, the location and installation of monitoring wells should address both existing and anticipated site development, including any predicted changes in groundwater flow. Few monitoring wells will endure for the full post-closure period of a landfill and consequently provisions are required for replacement or cleaning of wells.

Section 3.1 Hydrogeological Studies

Hydrogeological investigations are required to determine the appropriate placement of monitoring wells. Nearly all hydrogeological investigations include a subsurface borehole program which is necessary to define the hydrogeology and microgeology of the site. For boreholes that will be completed as monitoring wells, at least one groundwater sample should be collected from each lithological zone. Boreholes that will not be completed as monitoring wells must be properly decommissioned (i.e. back filled with impervious material). For further reference see **Guide for Decommissioning of Ground Water Wells, Vadose Zone Monitoring Devices, Boreholes and Other Devices for Environmental Activities** (ASTM D5299).

The number of boreholes required to delineate subsurface conditions will vary from site to site. Three holes are considered a minimum. On average, seven holes are about normal for sites with a relatively uniform lithology. There are exceptions (e.g. some sites may require as many as twenty test holes) but these would generally be installed over a multi-phase program (Piteau, 1990). Considerations for selecting drilling sites should include (Piteau, 1990):

- bore holes located both up and down gradient with respect to groundwater flow from a waste disposal site;
- bore holes drilled in both permeable zones and zones where low permeable material is expected;
- networks of holes to construct hydrogeologic profiles;
- potential use of test holes completed with piezometers to serve as permanent monitoring wells.

Hydrogeology of the uppermost aquifer and its confining layers should be characterised by installing wells, or piezometers, to determine:

- the direction and rate of groundwater flow (both horizontal and vertical). To determine a vertical rate, well placement must be in nests,
- seasonal/temporal, natural, and artificially induced short-term and long-term variations in groundwater elevations and flow patterns
- the hydraulic conductivities of the stratigraphic units at the site, including vertical hydraulic conductivity of the confining layers.

The local groundwater flow system can be determined by installing piezometers to measure the hydraulic heads at various points in the system. At least three piezometers in a triangular array are needed to define the horizontal hydraulic gradient and direction of groundwater flow in simple flow systems. Vertical gradients are determined with nested piezometers. In areas of complex geology, additional piezometers are needed since the flow medium will be heterogeneous and will result in a distorted hydraulic head distribution (Piteau, 1990).

Hydraulic head measurements should be collected at different depths, as well as at different locations on the site. Contours of the hydraulic heads will indicate which areas are located downgradient of the site and are therefore at risk of becoming contaminated, and which areas are located upgradient of the site and could thus provide background data. This information is useful for selecting appropriate monitoring sites (Piteau, 1990).

Section 3.2 Monitoring Wells

Groundwater monitoring wells are installed in and around a landfill site to permit water level measurement and sampling of groundwater and leachate. They are typically constructed of 50 mm diameter threaded polyvinyl chloride (PVC) plastic pipe with manufactured well screens (GLL, 1993).

All constructed wells should be tested to determine the hydraulic conductivity of the formation, and to determine if they are sufficiently responsive to the hydraulic flow system to provide reliable monitoring data.

3.2.1 Construction

Materials

Each monitoring program should be considered unique when determining monitoring well construction materials. The choice of construction material will depend on the following factors; cost, availability, strength, chemical and physical compatibility with analyte (the element or compound being tested for), groundwater and leachate. There is a variety of materials on the market with a wide price range. An assessment of material suitability for monitoring well construction is summarized in Appendix A.

Due to availability and cost, PVC tends to be the most common choice. However, recent studies investigating the adsorption and release of organic compounds by rigid PVC have led EPA to recommend the use of well construction materials made of polytetrafluoro-ethylene (PTFE) or stainless steel as opposed to PVC. Unfortunately, the costs of stainless steel and PTFE are five to seven times and ten to fifteen times, respectively, more expensive than PVC (Piteau, 1990). In certain cases it may be advantageous to design a well using more than one type of material. For example, where stainless steel may be preferred in a specific chemical environment, costs may be saved by using PVC in non-critical portions of the well. Additional components required for the monitoring well (e.g. primary filter pack, riser etc.) including joint/couplings should be comprised of material that will not alter the quality of water samples for the constituents of concern. With the exception of the primary filter pack, the additional components are commonly fabricated from PVC, stainless steel, fibreglass, or fluoropolymer. Materials recommended to prevent joints from leaking include PTFE tape for tapered thread joints and o-rings with a known chemistry for flush joint threads. Glued or solvent joints of any type are not recommended since glues and solvents may alter the chemistry of water samples (ASTM D5092-90). For further information regarding size specifications and/or installation procedures, refer to ASTM Designations: D 5092-90.

Methods

Well drilling methods commonly used in British Columbia include air rotary, cable tool, hollow/solid stem auger, sonic drilling and Becker hammer. The method selection is usually dictated by the expected ground conditions and the availability of equipment. Whenever feasible, drilling procedures should be utilized that do not require the introduction of water or liquid fluids into the borehole, and that optimize cuttings control at ground surface. Where the use of drilling fluids is unavoidable, the selected fluid should have as little impact as possible on the water samples for the constituents of interest (ASTM D5092-90). Furthermore, extreme care must be exercised when drilling at or near a geotechnical membrane liner (i.e.: a punctured liner would severely impact the effectiveness of the leachate collection system). It is the responsibility of both the driller and landfill operator to ensure that the monitoring well is installed correctly and that the integrity of the liner is maintained.

A matrix of appropriate drilling methods for use in British Columbia is presented in Appendix B. A further reference of greater scope and detail is **The Handbook of Suggested Practices for the Design and Installation of Groundwater Monitoring Wells** (Aller et al, 1989). It provides a matrix that uses a rating system to establish the desirability of a drilling method based on the general hydrogeologic conditions and well design requirements.

3.2.2 Design

Monitoring wells must include a protective casing that preserves the integrity of the borehole and be maintained to meet design specifications. This casing must be screened and packed with a filter to enable the collection of sediment-free groundwater samples. Well screen slot sizes should be based on hydrologic characteristics and on the grain-size distribution of the aquifer being monitored. The primary filter pack material should be a chemically inert material, well rounded and uniform in size. The most common filter packs are made of sand or gravel. At least two inches of filter pack material should be installed in the annular space and sealed above the sampling depth to prevent contamination of samples. The seals and grout are generally constructed of bentonite and/or cement, as appropriate. Refer to Appendix C for typical monitoring well design (EPA, 1993).

Groundwater monitoring wells can range in diameter from 25mm - 150mm, with a 50mm diameter the most common. The diameter of a monitoring well should be the minimum practical size which will allow for proper development of the well screen and operation of the sampling device. Large diameter wells (greater than 50 mm) are not recommended as they hold large volumes of water which require more purging prior to sampling.

Piezometers and wells should have as short a screened interval as possible for measuring total hydraulic head. Longer well screens (greater than 3m) may be warranted, in the following circumstances (EPA, 1993):

- when natural water level fluctuations dictate a longer screen length*
- when the interval monitored is slightly greater (thicker) than the appropriate screen length
- when a homogeneous, extremely thick aquifer (i.e. greater than 90m) is being monitored, a longer screen (i.e. 6m), representing a relatively distinct interval, may be necessary
- where soils with extremely low hydraulic conductivity are encountered

*Note: Use of nests with a screen length of 1.5m or less is recommended.

Screens can range in length from a few centimetres to tens of meters. They typically range from 0.5 - 1.5 m in length and are sealed in intervals slightly longer. Short screens provide discrete data while long screens have limited application. Longer screens obtain a sample that represents the "average" chemistry of water flowing through the aquifer and is a function of all of the different heads over the entire length of the screened interval.

3.2.3 Development

Well development is intended to correct any clogging or compaction that may interfere with water quality analysis, to improve hydraulic characteristics and to restore groundwater properties disturbed during the drilling process. Well development should follow the installation process and continue until the representative water is free of waste, or other materials introduced during the drilling process. Representative water is assumed to have been obtained when pH, redox potential (Eh), temperature, and specific conductivity readings have stabilized and the water is virtually clear of suspended solids (ASTM D5092-90). A well recovery test should be carried out immediately after and in conjunction with well development. Methods of development include mechanical surging, over pumping, air lift pumping and well jetting. The combined use of a jetting tool with air-lift pumping is a particularly effective development method. Mechanical surging, as with a surge block or large bailer, can also be used but is less effective (Sabel and Clark, 1985).

Section 3.3 Monitoring Locations

3.3.1 Background Monitoring

Up-gradient and down-gradient monitoring wells should be sampled at quarterly intervals as a minimum, and their individual analytical results used as a baseline for comparison. In this manner, natural variations in quality can be taken into consideration when interpreting monitoring program data.

In the case of a new facility, groundwater samples collected from both up-gradient and down-gradient locations prior to waste disposal can be used to establish background water quality. To account for both seasonal and spatial variability in groundwater quality, sampling should be conducted for a minimum period of one year.

In the case of an existing landfill, groundwater samples collected up-gradient can be used to establish background water quality. Historic well records can also be used as a data source, providing the methodology used to collect the data meets current Quality Assurance (QA) and Quality Control (QC) requirements. A minimum of one year is required to establish the ambient background (EPA, 1993).

3.2.2 Well Networks

In order to effectively detect and evaluate potential or existing groundwater contamination at a landfill, there are three principal locations for groundwater monitoring (Lu, 1985):

- A minimum of one well up-gradient from the landfill to establish background water quality, and to establish water level elevations and hydraulic gradients for determining groundwater flow into, or below, the landfill. Although one up-gradient well is the minimum, it is recommended that two up-gradient wells be installed to give some idea of background water quality variability.

- A well immediately adjacent to the down-gradient edge of the filled area, with screen intercepting the water table to enable sampling of 'raw' leachate for chemical constituents at the contaminant source and to measure fluid levels for determining leachate position in relation to the refuse.
- A line of three wells situated down-gradient from the landfill and perpendicular to groundwater flow in the horizontal plane to detect and determine the extent and concentrations of any leachate plumes; to assess groundwater levels, flow directions, and flow rates; and to assess leachate impacts on receptors (e.g. supply wells and receiving waters).

The size of the landfill, hydrogeologic environment, rate of groundwater flow, and budgetary restrictions are factors which will dictate the actual number of wells installed. The design of the monitoring system should take into consideration the following characteristics (EPA, 1993):

- aquifer thickness, flow rate, and flow direction (including seasonal and temporal fluctuations); and
- saturated and unsaturated geologic units and fill materials overlying the uppermost aquifer, including: thickness, stratigraphy, lithology conductivities and porosities.

3.3.3 Well Placement

Considering both contaminant characteristics and hydrogeologic properties is important when choosing the vertical and lateral placement as well as the screen length. To facilitate early contaminant detection, monitoring wells should be located to sample groundwater from the uppermost aquifer, at the closest practicable distance from the site boundary, encompassing all possible routes to detect leachate migration.

Monitors at up-gradient and down-gradient locations should generally be installed at two depths; one in the uppermost aquifer and a deeper one to assess vertical hydraulic gradients and the potential for leachate movement to depth. Monitoring wells installed through the refuse should generally be established within the refuse or in the uppermost aquifer below the base of the refuse. Deep monitors installed below the refuse frequently become contaminated by leachate moving down the borehole during drilling if appropriate precautions are not taken (GLL, 1993). Furthermore, extreme care must be exercised if drilling through the liner. Special precautions must be taken to protect the integrity of the liner.

Section 3.4 Hydraulic Conductivity

The hydraulic conductivity (K) of the various soil and underlying strata, should be determined by carrying out in-situ slug tests, grain size analyses, packer testing, pump testing or other means when the groundwater monitors are initially installed (GLL, 1993).

Section 3.5 Sampling and Measuring Methods

A sampling device is chosen based on the parameters that are to be monitored, the compatibility of the rate of well purging with well yield, the diameter of the well, and the depth from which the sample must be collected.

Appropriate measures are required to prevent cross contamination between drillholes during the sample collection procedure. For example, drilling equipment must be decontaminated between boreholes; sampling equipment must be decontaminated between each sampling event and where appropriate, between specific parameter groups such as organic contaminants. Sampling equipment (including automated models) must be made of materials that are compatible with the nature of the existing groundwater and the potential contaminants introduced via leachate.

The routine parameters monitored in groundwater include pH, redox potential (Eh), dissolved oxygen (DO), specific conductivity, metals, ammoniacal nitrogen, chloride and chemical oxygen demand (COD); other parameters may be added to this list on a site specific basis. For the monitoring of metals, the EPA recommends the following be monitored regularly; antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, lead, nickel, selenium, silver, thallium, vanadium and zinc. The standard industry practice is to use a flow through cell to measure the physical parameters. Routine quarterly sampling and in-situ monitoring will establish the presence of any trends, identify any statistically significant changes and, most importantly, identify those parameters with values greater than those of the criteria (EPA, 1993 and Barcelona, 1985).

"Statistically significant" refers to a statistically significant increase over background values or a compliance level for each parameter or constituent being monitored. It is the responsibility of the owner/operator to choose an appropriate statistical method consistent with the number of samples collected, and distribution pattern of the parameter. The statistical method must satisfy or be agreed to by the Ministry of Environment. Examples of appropriate statistical methods and performance standards are outlined in the EPA document **Criteria For Municipal Solid Waste Landfills**, Subpart E section 258.53 paragraphs (g) & (h) (EPA, 1993).

Section 3.8.2 of this guideline addresses the action required if irregularities are found in a monitored parameter.

3.5.1 Groundwater Flow

Groundwater elevations are used to determine horizontal and vertical hydraulic gradients for estimation of flow rates and flow direction. Groundwater elevations must be measured for each well immediately prior to purging. Groundwater elevations for all wells on site must be measured within a short enough period of time to avoid temporal variations in groundwater flow which could prevent accurate determination of rate and direction of flow. Changes of barometric pressure, in confined aquifers and, to some degree, in unconfined aquifers can also affect the exactness of groundwater elevation readings. In recognition of this potential impact, it is recommended that barometric pressure be measured at each monitoring well, and where appropriate, the data be corrected to enable other head level influences to be clearly identified. In addition, groundwater elevation readings should, where possible, take into account local interference caused by nearby pumping wells or heavy truck traffic near the monitoring well.

To adequately determine groundwater flow directions, the vertical component of groundwater flow should be evaluated directly. Proper selection of the vertical sampling interval using site specific hydrogeological data is necessary to ensure that the monitoring system is capable of detecting a contaminant release from the landfill. This generally requires the installation of multiple wells/piezometers, in clusters or nests, or the installation of multilevel wells or sampling devices (EPA, 1993). The following equation describes seepage velocity:

$V = Ki/ne$

V is the average lineal velocity

NE is effective porosity

i is the gradient

K is hydraulic conductivity

Due to seasonal variations in climate throughout British Columbia, the quantity of recharge to groundwater flow systems is not constant. A cycle of hydraulic head data is thus required before groundwater flow directions can be reliably determined. The ideal duration for a cycle is five years, the absolute minimum duration to be used is one year.
A sufficient number of piezometers or wells at appropriate locations and depths should be installed to gauge both seasonal average flow directions and temporal fluctuations in groundwater flow. Field measurements must include the following:

- depth to standing water
- total depth of the well
- thickness of immiscible layers (if present)

Static water level and the depth to the well bottom can be measured to the nearest 1 cm using electric water level tape or wetted steel tape. To prevent cross contamination of wells, water level measurement devices must be decontaminated prior to use at each well (Piteau, 1990).

3.5.2 Frequency

Sampling frequency is based on the rate of contaminant movement. Groundwater velocities are usually much less than those of surface waters, and therefore sampling intervals may be longer. Monitoring parameters and frequency of sampling are site specific.
Quarterly monitoring of water levels in all monitoring wells should be conducted to determine seasonal variations in groundwater flow. Water levels should be monitored on at least the same frequency as the regular chemical monitoring. Certain monitoring programs may involve more or less frequent sampling based on the expected rate of contaminant migration (EPA, 1993).

3.5.3 Purging

Water which has resided in a well casing for an extended period of time has the opportunity to exchange gases with the atmosphere and to interact with the well casing. Water standing in the columns inside the well casing must therefore be purged prior to sampling so that a representative sample can be obtained. To adequately purge a well, monitor the pH, redox potential (Eh), temperature, and conductance of the water during the purging process, and assume purging is complete when these measurements stabilize. Rather than specify a number of purge volumes for all wells, it is recommended that the approximate number be determined on a site specific basis according to field experience for the number of well volumes required to reach equilibrium.

Purging should be accomplished by removing groundwater from the well at low flow rates using a pump. Low flow rates are recommended so as not to disturb sediment collected in the bottom of the well casing. Because pumps can operate at variable speeds, some such as the submersible and bladder variety are considered particularly useful for purging stagnant water from a well. The use of bailers should generally be avoided as the 'plunger' effect of their use can result in the continual development or over development of the well. Descriptions of eight different kinds of pumps are presented in Appendix D.

Wells should be purged at rates less than or matching groundwater flow. A low purge rate, 0.2 - 0.3 L/min. or less, will reduce the possibility of stripping VOCs from the water and reduce the likelihood of mobilizing colloids in the subsurface that are immobile under natural flow conditions. For further information, refer to the designation guide ASTM D 4448-85a.

If contaminants are suspected in the groundwater prior to purging then appropriate disposal measures should be carried out. The purged groundwater should be tanked, tested and disposed of in accordance with established sanitary and stormwater sewer use criteria and other applicable regulatory requirements (EPA, 1993, Barcelona, 1985 and Kent, 1988).

3.5.4 Sample Extraction

The rate at which a well is sampled should not exceed the rate at which the well was purged. Low sampling rates, approximately 0.1 L/min., are suggested. Pumps should be operated at rates less than 0.1 L/min. when collecting samples for volatile organic compound analysis.

Sample withdrawal methods include the use of pumps, compressed air, syringe sampler, and bailers. The selection of the sampling method must be based on the parameters that are to be monitored, the depth from which the sample is collected and the diameter of the well (Piteau, 1990). The primary consideration is to obtain a representative sample of the groundwater body by guarding against mixing the sample with stagnant water in the well casing. This is avoided through adequate purging prior to collecting the sample. Refer to Appendix D for a description of a number of different samplers that are available to extract water for a variety of monitoring well diameters.

3.5.5 Vadose Zone Monitoring

Monitoring in the vadose zone can involve sampling of gases (primarily VOCs) or sampling of pore water. Sampling and analysis of soil gases can delineate VOC contamination or detect VOC leaks. VOCs migrate faster as vapours than as components in aqueous or liquid phases, and therefore are considered to be early indicators of hydrocarbon contamination. They can be measured using portable organic vapour analyzers or collected for laboratory analysis. If a portable unit is used (Piteau, 1990):

20. test pits can be used to penetrate to the VOC contaminated soil;
21. hollow pipes with perforated tips can be driven into the ground or installed with a drill and suction used to draw gas into a suitable container;
22. using a passive method, samplers can be buried in a manifold or a grid layout and be allowed to absorb VOCs for a given period of time.

Pore water sampling can provide early detection of contaminant leaks, or monitor attenuation processes. Pore water samples can initially be collected during drilling operations by collecting core samples in sealed tubes and having the appropriate analysis performed in a laboratory. Permanent sampling devices must be installed in the unsaturated soil to allow for collection of pore water samples on a regular basis. Lysimeters can be installed in drillholes and are the most extensively used device for sampling pore water (Piteau, 1990).

3.5.6 Sample Preservation

To assist in maintaining the natural chemistry of the samples, it is necessary to preserve the sample. Methods of sample preservation are relatively limited and are intended to reduce the effects of chemical reactions and the effects of sorption and to arrest biological action. Preservation methods are generally limited to pH control, absence of air, refrigeration, and protection from light.
Glass, stainless steel, Teflon or plastic (polyethylene and polypropylene) are the types of containers acceptable for most kinds of sample collection. There are some exceptions to this general rule; for example, plastic is not recommended for organics while stainless steel is not recommended for metals. Containers should be kept full until samples are analyzed to maintain anaerobic conditions. The sample container material should be non-reactive with the sample and especially with the particular analytical parameter to be tested. Sample containers used to transport samples to the lab must undergo pre-treatment procedures. Pre-treated containers may be purchased commercially; however, pretreatment is

necessary if they are re-used. For appropriate sample containers and preservation methods, refer to Appendix E.

Samples should be placed in bottles immediately upon collection, and where preservation of the sample is required it should be carried out immediately. Handling of the sample and contact with the atmosphere should be kept to a minimum. The samples should be properly packaged so as to prevent breakage and should generally be kept at 4°C +/- 2°C until analyses by the laboratory (BC Environment, Laboratory Services, 1994).

3.5.7 Quality Assurance and Quality Control

Monitoring programs should include a quality assurance (QA) and quality control (QC) component in their design, in order to provide confidence in the data obtained. Refer to the manual Quality Assurance in Water Quality Monitoring produced by Environment Canada for the development and implementation of acceptable water quality monitoring programs.

Laboratories generally have their own QC program consisting of regular testing of method blanks, method detection limits (MDLs), laboratory spikes, and laboratory duplicates and, although a critical component of the overall QA/QC of the program, are not further addressed as part of this guideline.

The QA is necessary to verify the reliability and accuracy of the combined field sampling/handling and laboratory procedures and should include the following (Piteau, 1990):

23. *blind replicate samples*: identical field samples are submitted under different sample identities to test for precision of the sampling and analytical procedure;
24. *blind reference samples*: reference samples (may be certified) are submitted under fictitious sample identities to test for analytical bias;
25. *spiked samples*: a field sample is split and a known concentration of a contaminant is added to one-half of the sample to check for systematic errors and bias;
26. *blank samples*: distilled/deionized water is carried through sample collection and handling (including preservation) to check for contamination, purity of preservatives and other systematic errors occurring from time of sampling.

Contaminant concentrations in field blanks should be recorded and carefully reviewed in comparison to field sample results in order to assess the degree to which sampling induced errors, if any, have contributed to a lack of accuracy or representativeness of the field results.

The laboratory should be contacted prior to sampling to ensure that sample handling, preservation and shipping methods are appropriate. Sample storage time prior to laboratory analysis must not exceed specified holding limits. Appendix F provides a generalized flow diagram of groundwater sampling steps.
The calibration and maintenance of field equipment is also an integral component of the QA/QC program. All equipment must be kept clean and in good working condition, using the techniques described by the manufacturer. Calibrations, prior to the sampling event, should be carried out under the same instrumental and chemical conditions as those that will exist at the sampling site. The frequency of calibration will depend on the accuracy requirements of the investigation and the stability of the instrument. To ensure a high standard of QA/QC, monitoring personnel must be adequately trained and supervised (Environment Canada, 1993).

Section 3.6 Organic Contaminant Sampling

Groundwater samples collected for analyzing organic constituents should not be field-filtered prior to laboratory analysis. The traditional recommended container for collection is an amber coloured glass with an aluminum foil or Teflon liner cap. Alternative methods are available, such as; a solid phase extraction disk and special vials for VOC sampling. For additional QA details refer to Appendix E (Barcelona, 1985).

3.6.1 Volatile Organic Compounds

Volatile organic compounds (VOCs) must be sampled in a manner which does not permit agitation or excess exposure to air. Pumps which induce suction pressure, such as peristaltic pumps, or which have lift devices, may aerate the sample and are not recommended for sampling VOCs. Positive displacement bladder pumps or bailers constructed entirely of fluorocarbon resin or stainless steel are preferred. The vial sampling protocol, (zero headspace extractor (ZHE) in the field), is also an effective method of sampling VOCs. VOCs should be the first sample that is collected following the purging process (EPA, Sept. 1986). During sampling, the pumping rate should be kept to a rate of less than 0.1 L/min. Samples should be placed directly in glass bottles, filled such that no air space remains and capped with a Teflon septum cap.

3.6.2 Extractable Organic Compounds

Samples for extractable organics should be collected after the VOC samples. Glass or Teflon bottles with Teflon lined caps should be used as sample containers (Piteau, 1990).

3.6.3 Immiscible Layers

Immiscible layers must be sampled before a well is purged. To determine the presence of an immiscible layer, an interface probe should be used to measure the first fluid level in a well. Once this has been recorded, it should be lowered until the immiscible water interface is encountered. The depth interval, or thickness, of a floating immiscible layer can then be established.

When dense non-aqueous phase liquids (DNAPLs) maybe present in the sample well, special methodologies must be incorporated into the drilling process. Contamination of deeper wells must be considered when drilling through DNAPL areas during drilling and sampling operations (Sara, 1994).

Section 3.7 Inorganic Contaminated Sampling

Where a gradient in sampling both organic and inorganic contaminants is anticipated, start at the least contaminated well first and work to the most contaminated well (Environment Canada, 1993).

3.7.1 Specific Conductance

Specific conductance and temperature should be measured in the field using portable equipment. Since landfill leachate generally has substantially higher temperature and specific conductance than natural groundwater, the presence of leachate can often be detected using a conductance-temperature probe. Specific conductance can be measured quickly and easily and is useful for estimating the total amount of inorganic dissolved solids. Specific conductance and pH should ideally be measured both in the field and in the laboratory. Additional parameters that should also be measured in the field include redox potential and dissolved oxygen (Environment Canada, 1994).

3.7.2 Metal Compounds

Groundwater samples collected for analyzing (total) metal contaminants should be collected in a plastic container and preserved with an acid solution prior to analysis. Groundwater samples collected for analyzing (dissolved) metal contaminants should be field-filtered under pressure, collected in a plastic container and preserved with an acid solution prior to analysis. Refer to Appendix E for appropriate preservation and collection techniques (BC Environment, Laboratory Services, 1994).

3.7.3 Inorganic Compounds

To avoid contamination, containers used for collecting groundwater samples for inorganic contaminants analysis should, in most cases, be adequately rinsed with the appropriate agent before the containers are taken to the field for use. For appropriate container and rinsing agents refer to Appendix E. Prior to sample withdrawal, the containers and caps should be rinsed twice with the water to be sampled (Barcelona, 1985).

Section 3.8 Data Analysis

Monitoring programs for landfills serving more than 5,000 people should store monitoring results in computerized electronic data bases which have the capability of carrying out statistical analyses on the data. While hard copy files containing complete chemistry and water level monitoring data are sufficient at present for monitoring programs serving populations of less than 5,000 people (i.e. small landfills), it is recommended that electronic data bases be used for these sites as well. It is anticipated that all regulatory data submitted to the Ministry will be requested in electronic format in the not too distant future. Monitoring data can be evaluated using the following methods; time base graphs and/or contour plots (Piteau, 1990).

3.8.1 Charts, Graphs, and Maps

Data tabulation and comparison to appropriate water quality criteria for drinking and aquatic uses shall be performed. At a minimum, the data should be compared to BC's Approved and Working Criteria for Water Quality. In addition, statistical comparisons between up-gradient and down-gradient wells should be carried out after receipt of validated data for each sampling event.

Information should be expressed in a manner that will aid interpretation of data. All relevant data charts, equipment performance records, calibration records, and maps should be constructed. Such data may include isopach maps of the thickness of the upper aquifer and important strata, isoconcentration maps of contaminants, flow nets, cross-sections, and contour maps. Below is a more complete list of methods in which data can be presented (GLL, 1993, EPA, 1993).

27. Water quality concentrations should be plotted versus time for selected parameters and sampling locations. This permits seasonal and temporal trends to be visually interpreted. Plots of annual mean values are sometimes useful for assessing long term trends which might otherwise be unrecognizable due to short term variability.
28. Surface water flow measurement should also be plotted versus time using the same scale time axis as the concentration plots, so that the influence of flow on water quality can be visually interpreted.
29. Groundwater quality data should be plotted on site plans and cross-sections constructed parallel or perpendicular to the direction of groundwater flow, so that the leachate plume can be defined in three dimensions.
30. Contour plots should generally be made of hydraulic head data plus selected contaminant indicators to show the direction of groundwater flow and the extent of any contaminant plumes.
31. A potentiometric surface map, or water table map, should be prepared for each water-bearing zone that comprises the uppermost aquifer showing both the direction and rate of groundwater flow and locations of all piezometers and wells on which they are based.
32. A groundwater flow map should be prepared annually and compared with previous years' results in order to identify any major changes in flow which may have occurred.

Owners / operators of larger landfills may wish to consider the use of a full range of data presentation methods, while a more selective subset of methods may be more appropriate for smaller landfills. The use of concentration plots and flow maps would satisfy minimum requirements.

3.8.2 Reporting

Monitoring reports in electronic format containing suitably tabulated groundwater quality data, quantity measurements and other monitoring data for inspection are to be submitted to the Regional Waste Manager within 30 days of each sampling term. Other records, reports or other information should be submitted within 30 days of the reporting period stipulated in the permit, unless otherwise specified (Piteau, 1990).

3.8.3 Remedial Action

Further monitoring is required whenever a statistically significant increase has been detected for one or more of the constituents or where the monitored value of one or more constituents is greater than that of the criteria. If such results are detected at any monitoring well, the following steps should be taken (WAC 173-304-490):

- inform the Ministry of Environment and place a notice in the operating record within two weeks of the finding, identifying which parameters have shown statistically significant changes from background levels and / or are higher than the criteria; and
- develop and implement an assessment monitoring program within three months for parameters which have shown statistically significant changes; or
- develop and implement a plan to mitigate the constituents which show values that are greater than those of the criteria; or
- demonstrate that a source other than the landfill caused the contamination; or
- provide evidence to prove the statistically significant increase or monitored constituent value thought to be higher than the criteria resulted from error in sampling, analysis, statistical evaluation or natural variation in groundwater quality.

Based on the results of the monitoring, a remedy should be selected that:

- is protective of human health and the environment;
- attains the groundwater protection standards;
- controls the source or release so as to reduce or eliminate further contaminant releases into the environment that may pose a threat to human health or the environment

Section 4.0: Surface Water Monitoring

Surface water monitoring should only be a routine component of a landfill monitoring program where leachate and/or concern with groundwater is known to or suspected of impacting on nearby surface water. Otherwise, monitoring is normally necessary at the outset and only infrequently thereafter.

Surface water monitoring at landfills is intended to detect unacceptable surface water contamination resulting from landfill operations. Acceptable contaminant levels are specified by the Manager and will generally be in accordance with the Approved and Working Criteria for Water Quality - 1995 , (BC Environment, 1994).

Section 4.1 Monitoring Locations

Surface water monitoring locations should include (GLL, 1993):

1. Upstream (Background) — to establish background water quality / bottom fauna conditions and flow;
2. Immediately Downstream (Pathway, Receptor) — to determine leachate impacts on water quality and bottom fauna at and immediately downstream of the landfill; and
3. Downstream Recovery (Receptor) — located further downstream to document the extent of the mixing zone and distance required for the surface water to assimilate leachate and for water quality to recover to background levels.

Section 4.2 Monitoring Frequency

Surface water monitoring frequencies should be higher than groundwater sampling frequencies in order to account for the greater flow; in general, a faster velocity means impacts will spread more quickly. The suggested minimum sampling frequency for surface water is six to eight times per year. However, in most cases the sampling frequency will depend on the goals/objectives of the monitoring program. For example, the assessment of annual trends would require monthly to more frequent sampling whereas, the assessment of a specific event (e.g. low flow period) would require that sampling be conducted only during its occurrence. Measurements of surface water flow should be taken whenever surface water samples or bottom fauna are collected (GLL, 1993).

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Section 4.3 Field Investigations

Water quality should be monitored in surface waters adjacent to landfill sites and compared with the ambient surface water background. Deterioration in water quality could indicate inadequate leachate containment or attenuation. Knowledge of surface water flow, quality and use, as well as aquatic biology information is valuable for assessing surface flow pathways and potential impacts on surface water receptors.

Surface water should be monitored for pH, redox potential, specific conductance, temperature and dissolved oxygen concentration. This range of parameters is usually sufficient to give an indication of any changes in inorganic water quality. Samples should always be collected on the same day as field measurements and during constant flow conditions (Environment Canada, 1994).

4.3.1 Bottom Fauna and Fish Surveys in Surface Waters

An indication of surface water quality can be obtained by carrying out a Biodiversity Index survey (e.g. fish and/or bottom fauna surveys). Studies indicate that certain bottom fauna and fish species (e.g. mayflies and stet) are very sensitive to contaminants in leachate and may not be present in normally anticipated species and numbers when under stress; conversely, there are other species (e.g. sludge worms and midge larvae) that may flourish in the stressed environment.

Surveys should be carried out by qualified individuals, in selected locations (i.e. upstream, adjacent and downstream of the landfill), and in areas of similar substrate and flow. Sampling methods include, but are not limited to, Surber sampler, seine net hauls, traps and electroseining.

The data collected from the bottom fauna survey can be used as direct measures of bottom receptors and represent the long-term surface water quality trends. Data collected from the fish survey provide the basis for correlating fish presence/absence with water quality information and allow meaningful interpretation of the significance of leachate impacts rather than inferred impacts based on fish toxicity literature (GLL, 1993).

4.3.2 Contaminant Loading Surveys

Contaminant loading surveys are best suited for sites where leachate is impacting on small- to medium-size streams. This type of survey attempts to identify background conditions and all upstream and downstream contaminant discharges. Measurements taken are: discharge flows, contaminant concentrations for parameters which are not attenuated or biodegraded (e.g. chloride) and background conditions. Sampling is usually carried out during a low flow period to assess the maximum impacts. Contaminant loading is calculated by multiplying the contaminant concentration by the flow rate. Due to conservation of mass, downstream loadings should equal the background loadings plus additional loadings from the contaminant source (GLL, 1993). Discrepancies could indicate an unidentified contaminant source, another diluting source (e.g.: a tributary stream) or sampling/analytical errors.

Section 5: Leachate Monitoring

Landfill leachate quality has proven to be highly variable in relation to location within the landfill and the age of the facility. Thus, the term "typical leachate" must be used with caution and in the context of a given type and age of landfill. In addition, the chemical characteristics of any leachate sample, regardless of its source, should not be considered representative of the total volume of leachate.

Section 5.1 Seep Detection

Small springs of discoloured, malodorous leachate, frequently found along the lower edges of many landfills, may be the only visible indication of landfill leachate migration. These typically represent only a small fraction of the total leachate generated by the landfill. Seeps may represent the intersection of the water table with the land surface, or they may be the discharge from a small perched water table within a landfill. Seeps are valuable for collecting concentrated leachate samples; however, the seep may not be representative of the total volume of leachate. Substantial changes in seep locations or flow rates and/or the sudden appearance of new seeps, are indicative of a change in the flow system within the landfill and should be investigated (Lu, 1985).

Section 5.2 Leachate Quality

Leachate composition is important in determining the potential impact on surface and groundwater quality. Leachate is a high strength, aqueous solution and is formed when water introduced with the waste or from external sources percolates through the landfill, contacting the waste.

Factors which can affect leachate quality include (Henry and Prasad, 1991 and Lu et al, 1985):

- age of wastes;
- type and chemical composition of wastes;
- climate and moisture regime including seasonal effects;
- waste processing and compaction and other landfill operational aspects;
- temperature, pH and redox condition in the landfill;

- presence of large quantities of municipal sewage sludge or industrial sludge or wastes;
- thickness of the refuse layer; and
- permeability, thickness, compaction and slope of daily and final cover.

As leachate migrates through the substrate, away from the landfill, its quality is renovated by a process referred to as natural attenuation. The degree of *natural* attenuation which occurs is dependent on many site-specific factors including the bacteria population**,** clay content, organic content, and permeability of the soil as well as groundwater quality, flow rates, temperature, pH, and redox conditions. Mechanisms of attenuation include: adsorption, biological uptake, cation and anion exchange reactions, dilution, filtration, and chemical precipitation reactions (Ontario Environment, 1981).

Section 5.3 Indicator Parameters

There is virtually an endless number of parameters that could be analyses to determine the constituents of leachate and their impact on surrounding water quality. However, it is more efficient and cost effective to chose a set of parameters which characterize the overall components within a landfill, are not subject to decomposition, and have measured values well above detection limits. The final selection of leachate parameters must be based on a comprehensive assessment of background water quality, the pure leachate quality (if available), as well as hydrogeologic influences.

The data collected from the indicator parameters will be used to establish the presence of trends and/or irregularities within the leachate and provide a standard against which irregularities detected in the baseline groundwater chemistry can be measured. If a statistically significant change (as outlined in Section 3.5) is observed in an indicator parameter, a plan for further investigation and corrective action should be initiated in accordance with section **3.8.3 Remedial Action**.

The list presented in Table 1 illustrates typical characteristics of leachate; the asterisk denotes those commonly used as indicator parameters (SWANA, 1991).

Table 1: Typical Leachate Characteristics (SWANA, 1991)

Constituents	Range (mg/L)
pH	5.3 - 8.5
COD (Chemical Oxygen Demand)	3,000 - 45,000
chloride	100 - 3,000
nitrite	5 - 40
ammonia nitrogen	10 - 800
specific conductance	
temperature	
water elevation	
sulphate	100 - 1,500
cyanide	<0.10
VOCs	
BOD (Biochemical Oxygen Demand)	2,000 - 30,000
TOC (Total Organic Carbon)	1,500 - 20,000
total suspended solids	200 - 1,000
organic nutrients	10 - 600
total phosphorus	1 - 70
ortho phosphorus	1 - 50
alkalinity as $CaCO_3$	1,000 - 10,000
total hardness as $CaCO_3$	300 - 10,000
calcium	200 - 3,000
magnesium	50 - 1,500
potassium	200 - 2,000
sodium	200 - 2,000
total iron	50 - 600

Section 5.4 Bioassay

Bioassays are used to determine the relative strength of a substance by measuring its effect on a test organism. Bioassays may be required, on a site specific basis, to establish the total toxicity of landfill leachate. For example, it may be necessary to conduct a bioassay on a seep.

(Bioassays are tests related to discharges to aquatic environments and may therefore be of limited applicability to typical leachate/groundwater systems.)

Section 5.5 Electromagnetic Profile

The electromagnetic (EM) method uses an electromagnetic frequency wave to provide a rapid measurement of the electrical conductivity of subsurface soil, rock and ground water. EM surveys conducted by trained personnel are a relatively quick and economical way of mapping conductive leachate migration. However, it must be recognized that there are limitations to this technique. For example, it provides only indirect information which must be confirmed by drilling and by soil or ground water sampling. In addition, certain targets (e.g. conductive anomalies) may be difficult to differentiate, and penetration is limited to the top fifteen to sixty meters of the site (Sara, 1993).

Section 6: Landfill Gas Monitoring

Landfill Gas (LFG) monitoring is intended to detect unacceptable gas emissions resulting from landfill operations. Methane (CH_4) and carbon dioxide (CO_2) are the major constituents of landfill decomposition gas; other gases present in trace quantities include non-methane organic compounds (NMOCs), hydrogen sulphide (H_2S), nitrogen (N_2), hydrogen (H_2) and oxygen (O_2).

All waste disposal sites should be monitored for the presence of landfill gas in order to determine if gas exists in concentrations which present an unacceptable risk to human health and the environment. The area between waste disposal sites and neighbouring properties should be monitored in order to determine if landfill gases are migrating in that direction in unacceptable concentrations. Areas potentially at risk both within and outside the site boundary are those areas providing an enclosed space in which gas may accumulate or a high permeability pathway along which landfill gas may migrate. Examples include site offices and buildings, monitoring wells, gutters, manholes and utility service corridors.

Landfill gas monitoring should be carried out on roughly a monthly basis to identify, in an effective and timely manner, any problems or potential problems before they occur, thus facilitating remediation through early warning. The actual frequency of monitoring should be sufficient to detect landfill gas migration based on subsurface conditions such as partial or complete capping, landfill expansion, gas migration control system operation or failure, construction of new or replacement structures, and changes in landscaping or land use practices (EPA, 1993).

The following parameters may also provide useful information for a monitoring assessment:

- gas probe pressure;
- ambient temperature;
- barometric pressure; and
- the occurrence of precipitation during sampling.

For example, falling barometric pressure may cause increased subsurface gas pressures and corresponding increased methane content as gas migrates more readily (EPA, 1993).

It is recommended that all sites be monitored for the presence of the constituents of landfill gas prior to waste being deposited. This will allow for identification of any background gas sources, thus avoiding any misinterpretation of future data.

All personnel involved in the monitoring and control of landfill gas must be trained and understand the problems and limitations of the monitoring equipment, the sampling methods, the dynamic and unpredictable nature of landfill gas and potential hazards posed by its accumulation.

Section 6.1 Preliminary Assessment

The site investigation will verify subsurface stratigraphy, locate the water table, identify the composition of the waste and determine the extent of the fill. Based upon those findings, a system of gas probes can be designed that will take into account the site conditions.

Preliminary gas migration studies should determine the following if natural barriers exist (EPA, 1993):

- that the fill does not and is not likely to contain methane concentrations in excess of 25% of the lower explosive limit;
- that any proposed development on or near the landfill site will not be at risk from methane; or
- to define the extent of the lateral migration of methane and to assist in determining the need for and design of methane control systems.

Section 6.2 Non-methane Organic Compounds

As mentioned previously, landfill gas is a collection of air pollutants, including methane, carbon dioxide and non-methane organic compounds (NMOCs). The Ministry of Environment regulates landfill gas collection and treatment on the basis of annual emissions of NMOCs. The MSW landfill criteria require landfills emitting greater than 150 tonnes/year of NMOCs to collect and manage landfill gas. The formula used to calculate actual/expected annual NMOCs emissions can be found in Schedule II of the "Landfill Criteria for Municipal Solid Waste" (BC Environment, 1993). Periodic monitoring of NMOCs will assist in validating the model predictions of NMOCs emitted. In addition, the owner/operator is also required, for health and safety concerns, to regularly monitor the concentration and migration of methane, CO_2, H_2S, O_2 and percent lower explosive limit (%LEL).

To test for NMOCs, a probe with perforations at one end is augured to a depth of just less than 1 m below the base of the landfill cover. Landfill gas is extracted from the landfill through the probe at a rate of 100 ml/min. utilizing an evacuated cylinder. Analysis is carried out by gas chromatography techniques to allow constituent NMOCs to separate from other major gas components prior to measurement.

Concentrations of N_2 greater than 1% in the sample, indicate improper probe installation or sampling technique. This method is used to check the integrity of the sample. A gas sample is injected into a gas chromatograph and N_2 concentration is determined by a thermal conductivity detector.

Section 6.3 Acceptable Levels

Methane in the atmosphere in concentrations of 5% to 15% forms an explosive mixture that can pose a hazard to or in buildings, sewers, or other structures close to landfills. A concentration of 5% methane in the air is "the lower explosive limit" (LEL), and concentrations equal to or greater than the LEL are considered hazardous.

It is considered that concentrations greater than 25% of the LEL in on-site and off-site structures, or concentrations that exceed the LEL in soils at the property boundary, warn of conditions which could be potentially hazardous. Gas control systems should be designed to maintain concentrations well below these levels.

Hazardous conditions are not considered to be present on a landfill, when methane concentrations are less than 25% of LEL in facility structures, and when the concentration of methane gas does not exceed the LEL (5% by volume) at the property boundary. (Landtec, 1994; Ontario Ministry of Environment, 1987).

Current air quality standards for methane, CO_2, H_2S, and NMOCs can be obtained by contacting the Ministry of Environment, Environmental Quality Branch.

Section 6.4 Monitoring Locations

Gas probes should be installed in the more permeable strata, between the landfill unit and either the property boundary or structures where gas migration may pose a problem. Multiple or nested probes are useful in defining the vertical configuration of the migration pathway (EPA, 1993).

Monitoring and alarm devices for methane should be installed within, beneath, and immediately adjacent to structures, and in any associated utility service conduits and trenches. These devices should be used where there is any possibility that methane could exceed 25% LEL at any time. Where gas control facilities are required to protect a structure, this type of monitoring array will be required to insure that control facilities maintain methane concentrations below 25% LEL.

Section 6.5 Monitoring Frequency

Migration patterns and methane concentrations of landfill gas change rapidly. Where landfill gas emissions have been identified as a problem and/or where landfill gas is collected and managed, the following frequency is recommended: daily monitoring for H_2S and monthly monitoring for NMOCs, CO_2, methane, nitrogen and O_2.

At sites where there is a high degree of concern about gas migration endangering residences, daily measurements of H_2S and combustible gases should be conducted until the critical period has passed. Longer periods of monitoring are needed to assess adjacent property than are needed to assess areas underlain by wastes.

To safely assess the influence of seasonal variations on the migration and concentration of methane in the subsurface, two years of monitoring is recommended (EPA, 1993, EPA, 1994 and Landtec, 1994).

Section 6.6 Sampling Methods

Catalytic sensors are commonly used to detect methane concentrations less than the LEL. These devices function poorly in anaerobic conditions without a special attachment. Thermal conductivity sensors should be used when methane concentrations greater than the LEL are expected.

Methane concentrations and landfill gas pressure measurements in a monitoring well may be influenced by changes in barometric pressure. There may be a delay of several hours for equilibration to occur and this should be taken into consideration when assessing the collected data.

According to Landtec (1994), the minimum landfill gas system monitoring requirement consists of measurements of methane and barometric and static pressure. Oxygen and carbon dioxide are often measured as well but are optional, related to site specific concerns. Common portable instruments for pressure and methane measurements include a micromanometer or magnahelia (pressure), a combustible gas meter (% LEL methane) and a flame ionisation detector (FID) if methane readings in the low ppm are desired. FID instrumentation should be avoided if methane concentrations are unknown or suspected to be in the LEL to Upper Explosive Limit (UEL) range (Landtec, 1994 and EPA, 1993).

Section 6.7 Probe Installation

Probes are used to detect the migration of methane gas in the formations around a landfill. The probe is installed by boring a hole into the ground to at least the same depth as the deposited waste. A perforated pipe is placed into the hole and the space between the original soil and pipe is filled with sand. Clay is packed around the pipe near the ground surface to prevent air leaking into the probe.

Two types of measurements are conducted (Waste Age, 1986):

8. gas pressure is measured with a gauge or manometer; and
9. concentration of methane in the soil atmosphere is measured with a calibrated meter.

It may be best to install initial probes deep enough to verify the water table and to assess stratification. Subsequent probes may then be placed taking site specific conditions into consideration. It is advisable to install gas probes at various depths where the unsaturated layer adjacent to deep landfills is thick.

Section 6.8 Decommissioning Circumstances

Field data must be accurately collected in order to assess any hazards and assess the continuation or termination of gas monitoring facilities.

After two full years of monitoring during which the levels remain below 25% LEL, monitoring may be reduced and after a period of five years of periodic monitoring, the system may be decommissioned if levels remain below 25% LEL.

Passive gas control facilities require maintenance or periodic inspection for proper operation. Gas monitoring facilities that rely on passive gas control systems for safety cannot be decommissioned unless it can be demonstrated that maintenance or inspection is not necessary (Ontario Ministry of Environment, 1987).

Section 6.9 Ambient Air Quality Monitoring

Ambient air quality monitoring may be necessary to help justify (or not) a landfill gas management system, for those situations in which landfill gas is suspected of being a problem (i.e.: through the presence of odours, through indications of sub-surface migration, etc.) or for the collection of routine air quality data in the vicinity of the landfill. A typical monitoring program would include the collection of air samples at pre-determined locations and probe heights based on meteorological conditions at the site over an appropriate time period (8 hours, 24 hours, etc.).

Ambient conditions including temperature, barometric pressure and precipitation events should be recorded. Gaseous parameters analyses would include methane, H_2S, and NMOCs.

Section 7.0: Soils and Vegetation

Areas of vegetation toxicity or stress such as discoloration, die-off, stunting or anomalous growth may indicate leachate or landfill gas have migrated to the root zone. Landfill gas can damage vegetation due to the elimination of oxygen from the root zone of plants or due to the presence of a number of trace contaminants.

Soil analysis can be used for tracing leachate constituents, particularly those prone to cation exchange or other adsorption reactions which cannot be obtained from water samples (GLL, 1993). Soils sampling programs involve the consideration of not only how to sample but where to sample and how many samples to take. As municipal solid waste landfills are one of the most complex sources of contaminants, it is imperative that soils sampling programs be designed and carried out by qualified personnel, including, in some cases, a statistician, to ensure that the results are representative and cost-effective.

It is recommended that an agrologist or plant biologist be consulted to determine the effect and, if required, remediation of LFG and/or leachate on soil and vegetation.

Section 8.0: Monitoring Program Management

Each monitoring program should be reviewed on an annual basis to determine if the monitoring objectives are being achieved. It might be necessary to modify the current program to analyze for additional contaminants in existing wells, to provide additional monitoring wells, to reduce contaminants and/or wells based on results in hand and/or combinations of these activities. The ultimate goal of the annual review is to keep the monitoring program cost-effective and consistent with environmental protection. This review and modification process should be considered an important part of every monitoring program. It is recommended that all monitoring data and associated reports be prepared and/or reviewed by qualified personnel designated by the permittee prior to submission to the Ministry to ensure consistency with the requirements of the program in place (Environment Canada, 1993).

Section 9.0: References

Aller, Linda et al. **Handbook of Suggested Practices for the Design and Installation of Groundwater Monitoring Wells.** Appendix B, pg. 324-366. National Water Well Association, 1989.

American Standards for Testing and Materials. **Annual Book of ASTM Standards.** Volume 11.01, Water and Environmental Technology. Designation: D3370-82. Philadelphia, PA. 1991.

American Standards for Testing and Materials. **Annual Book of ASTM Standards.** Volume 11.04, Water and Environmental Technology. Designation: D5088-90. Philadelphia, PA. 1991.

American Standards for Testing and Materials. **Annual Book of ASTM Standards.** Volume 11.04, Water and Environmental Technology. Designation: D4448-85a. Philadelphia, PA. 1992.

Barcelona, M.J. et al, September 1985. **Practical Guide for Groundwater Sampling.** EPA/600/2-85/104, US EPA, Roberts S. Kerr Environmental Research Laboratory, Ada, Oklahoma.

British Columbia Environment. **Approved and Working Criteria for Water Quality**. Ministry of Environment, Lands and Parks. Environmental Protection Department, Water Quality Branch. 1995.

British Columbia Environment. **British Columbia Environmental Laboratory Manual.** Ministry of Environment, Lands and Parks. Environmental Protection Division, Laboratory Services. 1994.

British Columbia Environment. **Landfill Criteria for Municipal Solid Waste**. Ministry of Environment, Lands, and Parks. Environmental Protection Division, Municipal Waste Reduction Branch. 1993.

Environment Canada. **Quality Assurance in Water Quality Monitoring.** Gaskin, James E.. Minister of Supply and Services Canada, 1993.

Environmental Protection Agency. **Solid Waste Disposal Facility Criteria - Technical Manual.** EPA 530-R-93-017 US EPA, November 1993.

Everett, Lorne G., Ph.D. **Groundwater Monitoring.** Guidelines and Methodology for Developing and Implementing a Groundwater Quality Monitoring Program. Genium Publishing Corporation. 1984.

Gartner Lee Limited. **Leachate Assessment Field Manual.** Prepared for Ministry of Environment, Lands and Parks. Skeena Region. February 1993.

Henry, Glynn and Durga Prasad. **Anaerobic Treatment of Leachate.** Paper presented at a seminar on leachate treatment and disposal, sponsored by the Pollution Control Association of Ontario and the Ontario Ministry of Environment. Toronto, Ontario. 1991.

Kent, Robert, and Katherine Payne. "Sampling Groundwater Monitoring Wells: Special Quality Assurance and Quality Control Considerations". **Principles of Environmental Sampling.** Chapter 15. Lawrence Keith, Editor. 1988.

Landtec. **Landfill Gas System Engineering Design: A Practical Approach.** , Landfill Control Technologies, Commerce, CA, 1994

Lu, James C.S., Bert Eichenberger, and Robert J. Sterns. **Leachate from Municipal Landfills: Production and Management.** Noyes Publications. 1985.

National Association of Waste Disposal Contractors. **NAWDC: Creating a Better Environment.** NAWDC Codes of Practice for Landfill. August 1989.

Ontario Ministry of Environment and Energy. **Guidelines for the Establishment, Operation, Management, Maintenance and Closure of Landfilling Sites in Ontario**. Publications Ontario. 1981.

Ontario Ministry of Environment and Energy. **Guideline for Assessing Methane Hazards from Landfill Sites.** November 1987.

Piteau Associates Engineering Limited. **Groundwater Quality Monitoring Manual.** Prepared for BC Ministry of Environment, Environmental Protection Division. March 1990.

Sara, Martin N. **Standard Handbook for Solid and Hazardous Waste Facility Assessments.** Lewis Publishers. 1994.

Sabel, G and Clark, T. **Procedures for Ground Water Monitoring.** Minnesota Pollution Control Agency Guidelines. April 1985.

Solid Waste Association of North America. **Manager of Landfill Operations Training Course.** Course manual. Publication # MSW-D 2360 GMISC 0005. Silver Spring, Maryland. Revised June 1991.

State of Washington. **Criteria for Municipal Solid Waste Landfills.** Washington Administration Code. Chapter 173-351. OTS Version.

State of Washington. **Minimum Functional Standards for Solid Waste Handling.** Chapter 173-304 WAC.

United States. **Federal Register.** Vol. 56, No.104. May 1991. Proposed Rules. Environmental Protection Agency.

United States. **Procedures Manual for Groundwater Monitoring at Solid Waste Disposal Facilities**. Environmental Protection Agency. 1977.

United States. **RCRA Groundwater Monitoring Technical Enforcement Guidance Document.** Environmental Protection Agency. NWWA/EPA Series. Printed by NWWA. Dublin, Ohio. September 1986.

United States. **Solid Waste Disposal Facility Criteria.** Environmental Protection Agency. Technical Manual. November 1993.

Waste Age. University of Wisconsin/Waste Age. **Landfill Course.** January 1986.

General References

The following references are provided here as supplementary reading material for the groundwater monitoring component of the Guidelines for Environmental Monitoring at Municipal Solid Waste Landfills. These references are not directly cited in the document.

United States. **Handbook: Ground Water, Volume I & II; Ground Water and Contamination & Methodology**. Environmental Protection Agency. September 1990.

The following references are from American Standards for Testing and Material (ASTM). **Ground Water**. 1993.

- C 136, Method for Sieve Analysis of Fine and Course Aggregates
- C 150, Specification for Portland Cement
- D 653, Terminology Relating to Soil, Rock and Contaminated Fluids
- D 1498, Standard Practices for Oxidation-Reduction Potential of Water
- D 1586, Method for Penetration Test and Split Barrel Sampling of Soils
- D 1785, Specification for Poly (Vinyl Chloride) (PVC) Plastic Pipe, Schedules 40, 80 and 120
- D 4380, Test Method for Density of Bentonitic Slurries
- D 4750, Test Method for Determining Subsurface Liquid Levels in a Borehole or Monitoring Well (Observation Well)
- D 5092, Practice for Design and Installation of Ground Water Monitoring Wells in Aquifers
- D 5299, Guide for Decommissioning of Ground Water Wells, Vadose Zone Monitoring Devices, Boreholes and Other Devices for Environmental Activities
- F 480, Specifications for Thermoplastic Water Well Casing Pipe and Couplings Made in Standard Dimension Ratio

Appendix A: Recommendations for Screen and Casing Materials in Sampling Applications (in decreasing order of preference)

Material	Applications	Other Considerations	Approximate Cost (Relative to PVC)
Fluorinated Ethylene Propylene (FEP)	Recommended for most monitoring situations where corrosive environments are anticipated. Also offers good chemical resistance to volatile organics.	Lower strength than steel and iron. Not readily available in British Columbia.	*
Polytetraflorethylene (PTFE) or Teflon (R)	Recommended for most monitoring situations with detailed organic analytical needs, particularly for aggressive, organic leachate impacted hydrogeological conditions. Virtually an ideal material for corrosive situations where inorganic contaminants are of interest.	Low strength, not readily available in British Columbia.	10 to 15 x

Kynar	Strong material that is resistant to most chemicals and solvents.	Poor chemical resistance to keytones and acetone. Not commonly available.	*
Fibreglass	Historically, fibreglass has not been used for monitoring wells due to potential leaching of epoxy resins. Recent advances in fibreglass technology have created a material that is equivalent to or more inert than Teflon, but is also very strong.	High strength, not readily available in British Columbia.	2 to 5 x
Stainless Steel 316 (flush threaded)	Recommended for most monitoring situations with detailed organic analytical needs, particularly for aggressive, organic leachate impacted hydrogeologic conditions.	High strength, reasonable availability. May be source of Cr, Fe and Ni in low pH environments.	7 x
Stainless Steel 304 (flush threaded)	Recommended for most monitoring situations with detailed organic analytical needs, particularly for aggressive, organic leachate	High strength, reasonable availability. May be source of Cr, Fe and Ni in low pH	5 to 6 x

	impacted hydrogeologic conditions.	environments.	
PVC (flush threaded or other non cemented connections)	Recommended for monitoring situations where inorganic contaminants are of interest and it is known that aggressive organic leachate mixtures will not be contacted. Cemented installations have caused documented interferences. The potential for interaction and interferences from PVC well casing in contact with aggressive aqueous mixtures is difficult to predict. PVC is not recommended where ppb or corrosive concentrations of organic contaminants are expected.	PVC can be used as casing with stainless steel screens for composite well. Moderate strength, good availability. Deteriorates when in contact with ketones, esters and aromatic hydrocarbons.	1 x
Acrylonitrile Butadiene Styrene (ABS)	Not commonly used for groundwater monitoring.	Lower strength than steel and iron. Not readily available except in domestic plumbing format which is not	*

		generally suitable for plezometer applications.	
Polypropylene	Resistance to mineral acids and moderate resistance to alkalis, alcohols, ketones and esters make polypropylene a suitable material for many applications. It deteriorates when in contact with oxidizing acids, aliphatic hydrocarbons and aromatic hydrocarbons.	Low strength, not readily available in British Columbia.	*
Polyethylene	Polyethylene is less reactive than PVC but more reactive than PTFE.	Low strength, not commonly available in format other than flexible water line.	*
Low-carbon Steel Galvanized Steel Carbon Steel	May be superior to PVC for exposures to aggressive aqueous organic mixtures. These materials must be very carefully cleaned to remove oily manufacturing residues. Corrosion is likely in acidic, high TDS environments, particularly when sulfides are present.	High strength, good availability.	1 1/4 to 3 x

Products of corrosion are mainly Fe and Mn, except for galvanized steel which may release Zn and Cd. Weathered steel surfaces present very active adsorption sites for trace organic and inorganic chemical species.

Appendix B: Drilling Methods Common to British Columbia

	DRILLING METHODS						
	Hollow / Solid Stem Auger	Sonic Drilling	Air Rotary	Mud Rotary	Downhole (Becker) Hammer	Cable Tool	Backhoe Excavation
Applicable Geology							
Surficial Sediments	X	X			X	X	X
Fine Granulated Sediments	X	X		X			
Soft Rock				X			
Cohesive Sediments	X	X		X			
Unconsolidated Sediments	X	X	X				
Bedrock			X		X		
Soft to Mod. Dense Sediments		X					

Maximum Depth (m)	30	60	> 60	18-20	40-45	60	5
Avg. Hole Diameter (mm)	150-200	175	150-200	110	150	150	150

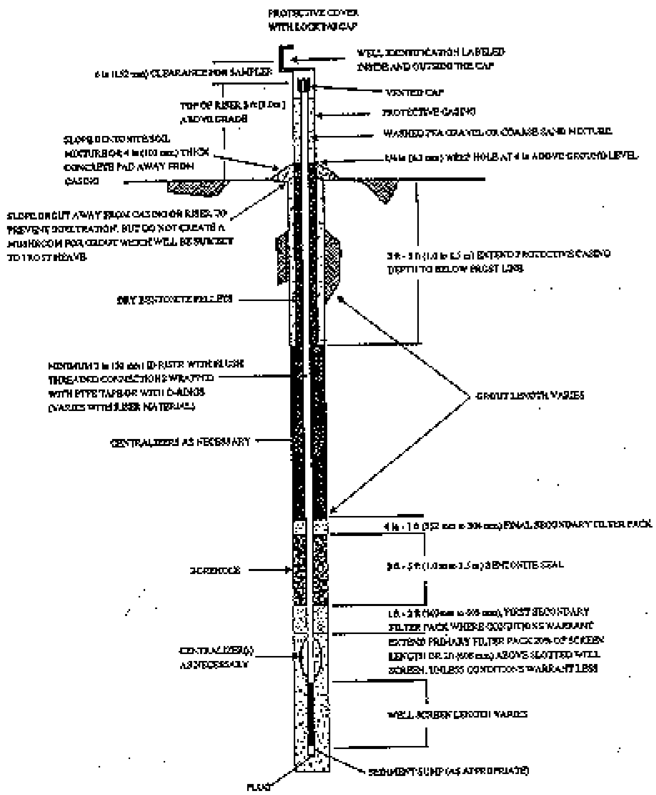
X means the most common geology for the drilling method specified; a blank does not denote that method cannot be used. Note: not all methods appropriate for all soil geology or for insertion of monitoring or drinking water wells. Please consult with professionals in drilling methods before proceeding.

Guidelines for Environmental Monitoring at Municipal Solid Waste Landfills

Appendix C: Typical Monitoring Well Design

Appendix C

Typical Monitoring Well Design



Monitoring Well Design - Single Cased Well *

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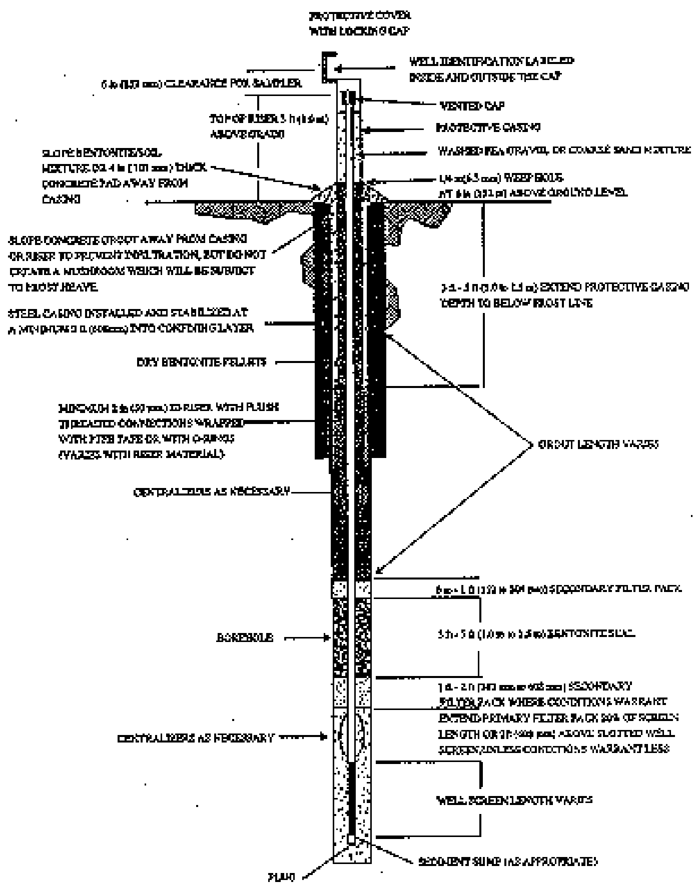
Appendix C



Monitoring Well Design- Multi-Cased Well *

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Monitoring Well Design - Multi-Cased Well*

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Appendix D: Sampling Equipment*

Sampling Devices	How the Sampling Device Operates	Pumping Rates	Characteristics	Disadvantages
Air Lift Pump	An air lift pump collects a water sample by bubbling a gas at depth in the well or tube.	Pumping rates depend on the size of the pump being used and how many pumps are used for each well.	Air lift sampling can be useful in monitoring wells that need to be pumped only at periodic intervals.	Air lift methods result in considerable sample agitation and mixing in the well.
Submersible Pump	Water is transported to the surface by centrifugal action through an access tube.	Vary from 26.5 - 53.0 Lpm depending upon the depth of the pump.	A submersible pump provides higher extraction rates than most other methods.	Considerable sample agitation and the potential introduction of trace metals into the sample from pump materials results.
Suction Lift Pump	Suction lift can be categorized as direct line, centrifugal and peristaltic.	Vary from 19 - 151 Lpm for direct line method. Approx. 3.7 Lpm for peristaltic pump method.	Suction life approaches offer a simple retrieval method for shallow monitoring.	Degassing and agitation occur as a result of suction lift.
Bladder Pump	Water enters the flexible membrane through the lower check valve; compressed gas	The 4.4 cm pump is capable of providing samples (approx. 2.6 - 5.6	Bladder pumps prevent contact between the gas and water sample and can	The large gas volumes required, especially at depth, potential bladder rupture, and

	is injected into the cavity between the stainless steel housing and the bladder.	Lpm) from depths in excess of 76 m.	be fabricated entirely of Teflon and stainless steel.	the difficulty in disassembling the unit for thorough cleaning.
Gas Displacement Pump	A column of water under linear flow conditions is forced to the surface without extensive mixing of the pressurized gas and water.	Flow rates of about 2.8 Lpm at 36.5 m are possible with a standard 3.7 cm inner diameter by 4.57 cm long pump.	Gas displacement pumps provide a reliable means for obtaining a highly representative groundwater sample.	Possibility of gas water interface, a degree of mixing, and sample degassing can occur during transport.
Gas Piston Pump	A double piston pump utilizes compressed air to force a piston to raise the sample to the surface.	Pumping rates of 0.5 Lpm have been reported from 30.5 m; sampling depths of 152 m are possible.	The gas piston pump provides continuous sample withdrawal at depths greater than is possible with most other approaches.	Contribution of trace elements from the stainless steel and brass is a potential problem.
Packer Pump	The hydraulic activated packers are wedged against the casing wall or screen, the sampling unit collects water samples only from the isolated portion of the well.	Vertical movement of water outside the well casing during sampling is possible with packer pumps but depends upon the pumping rate and subsequent disturbance.	A packer assembly allows the isolation of sampling points within a well.	Deterioration of the expandable material will occur with time, thereby increasing the possibility of undesirable organic contaminants entering the water sample.

Inertial Lift Pump	The operating principle of the pump is based on the inertia of a column of water contained within a riser tubing.	Pumping rates of between 0.05 to 10.0 Lpm have been recorded.	The inertial pump is inexpensive and offers multiple uses for groundwater monitoring wells.	The tubing coils, though reasonably lightweight, are stiff and may be awkward to transfer from well to well.

***Text extracted from Appendix D, Piteau (1990), from R.D. Morrison (1983).**

Appendix E: Sample Container and Preservation Criteria

Type of Analysis	Size	Type	Preservation	Hold Time
Water - Bacteriology				
Coliform, fecal and / or total	250 ml	P, ster	4 deg. C, do NOT freeze	48 hours
Standard plate count	250 ml	P, ster	4 deg. C, do NOT freeze	48 hours
BOD	1 L	P	4 deg. C, exclude all air	48 hours
BOD & TSS	2 L	P	4 deg., C, exclude all air	48 hours
Chlorophyll / Phaeophytin	membrane or GF / C Filter		store frozen in dark, with dessicant	N/A
Microtox	100 ml G, a		4 deg. C, exclude all air	5 days
Bioassay, Daphnia	4 L P		4 deg. C, exclude all air	5 days
Water - Inorganic Analysis		Container size is determined by the type and number of analysis		

General chemistry and anions	1 to 4 L	P	keep cool 4 deg. C	72 hours
Mercury, total	1 L or 500 ml	G, L (MERCURY)	6 ML 10% K2Cr2O7+6 ml H2S04 per L	28 days
Metals, dissolved	250 ml	P, L	field filter & press HNO3 tp pH < 2	6 months
Metals, total	250 ml	P, L (METALS)	pres HNO3 to pH <2	6 months
Carbon TIC / TOC, Inorg / org	100 ml	P or G	4 deg. C	72 hours
Chemical Oxygen Demand, COD	250 ml	P	0.2 ml H2SO4 / 250 ml	72 hours
Cyanide, SAD and / or WAD	1 L	P	NaOH to pH > 12	72 hours
Oil & Grease	1 L	G	HCL to pH <2	28 days
Phenolics, total	1 L	G, A	H3PO4 to pH 4+5 ml 20% CuSO4	72 hours
Phosphorus, Low level	100 or 250	G, A, R	keep cool, 4 deg. C	72 hours
Sulphide, total	500 ml	P or G	1 ml 2N Zinc Acetate, exclude air	72 hours

Water - Organic Analysis

AOX (Adsorbable Organic Halides)	500 ml	G, A, R, B	pH to <2 with HNO3	30 days
Chlorophenols PCP, TTCP, TCP	1 L	G, A, Solv	4 deg. C	30 days
Dioxins / Furans	3 x 1 L	G, A, Solv	4 deg. C	30 days
EPA 624, Volatiles or BTEX	3 x 40 ml	vial, G, B, P & T	headspace-free, 4 deg. C (Na2S203 if chlorinated)	14 days
EPA 625, CP / OC / PAH / PCB	1 L	G, A, Solv	4 deg. C	30 days
AEH, TCMTB	1 L / analysis	G, A, Solv	4 deg. C	30 days
Hydrocarbons	500 ml	G, A, Solv	4 deg. C	30 days
Copper quinolate (copper 8, PQ-8)	250, 500 ml		4 deg. C, HCL to pH <2	30 days
Resin Acids	1 L	G, A, Solv	4 deg. C, NaOH to pH 12	21 days
Trihalomethanes	500 ml	G, A, Solv	Na2S203, headspace-free, 4 deg. C	14 days
IPBC / DDAC	1 L	P or G	4 deg. C, 6N HCL, 2 ml/L	14 days

Soils, Sediments, Tissues and Others

Asbestos, bulk identification	50 g	whirl-pak		6 months
EOX, Extractable Organic Halides	50 g min	G, Solv, Fc	keep cool, 4 deg. C	6 months
Metals	100 g min	P, W (T)	keep cool, 4 deg. C	6 months
Organic Carbon	100 g mkin	P or G	keep cool, 4 deg. C	6 months
Organics - Semivolatile	200 g min	G, A, W, Solv	keep cool, 4 deg. C	6 months
Organics - Volatile	50 g min	G, W, Solv, B	keep cool, 4 deg. C	14 days
Particle Size Analysis	100 g dry wt	P or G	keep cool, 4 deg. C	6 months
PQ-8 (copper 8, copper quinolate)	100 g min	G (A), W, Solv	keep cool, 4 deg. C	6 months

Analysis with Limited Shelf Life

pH, Turbidity, Acidity, Alkalinity	72 hr
Ammonia, TKN, Nitrate, Nitrite	72 hr

P ortho, total, total dissolved	72 hr
Specific Conductance	72 hr

Legend

P = plastic	Ster = sterilized	B = baked
G = glass	Solv = solvent cleaned	T = tissue cup
A = amber	Fc = foil lined cap	
W = wide mouth	R = acid rinsed	

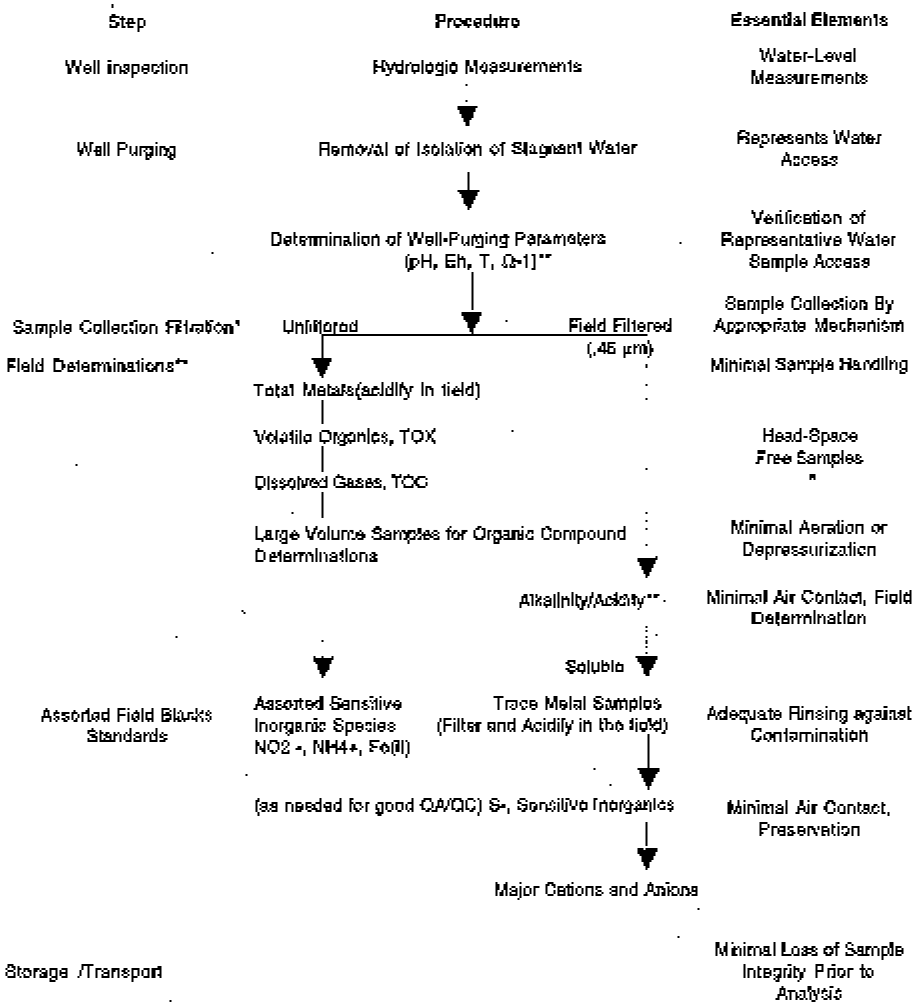
L () = labelled (description)

P & T = purge and trap vials

Appendix F: Generalized Flow Diagram of Groundwater Sampling Steps

APPENDIX F

Generalized Flow Diagram Of Groundwater Sampling Steps



*Denotes samples which should be filtered in order to determine dissolved constituents. Filtration should be accomplished preferably with in-line filters and pump pressure or by N2 pressure methods.

Samples for dissolved gases or volatile organics should not be filtered.In instances were well development procedures do not allow for turbidity-free samples and may bias analytical results, split samples should be spiked with standards before filtration.

Both spiked samples and regular samples should be analyzed to determine recoveries from both types of handling.

**Denotes analytical determinations which should be made in the field.

(Modifed Piteau 1990, Fig.5.7)

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(Modified Piteau 1990, Fig. 5.7)