12.0 GROUNDWATER MODELLING AND ASSESSMENT OF LONG-TERM GROUNDWATER IMPACTS

Groundwater and contaminant transport modelling were completed to simulate post-development conditions considering the planned Site development. Predictive simulations of groundwater quantity were completed using a three-dimensional (3-D) numerical groundwater flow model, while predictive simulations of contaminant transport and groundwater quality were completed using a one-dimensional (1-D) analytical contaminant transport model. The objective of the groundwater modelling studies described below was to quantitatively evaluate the potential effects of the Site on groundwater quantity and quality.

12.1 Hydrogeological Conceptual Model

12.1.1 Site Geological Setting

A detailed description of the local and regional geological setting for the Site is described in detail in Section 3.0. The following sections summarize the components of the Site geological setting pertinent to the development of the hydrogeological conceptual model.

The region within which the CRRRC Site is situated is characterized by relatively thick deposits of sensitive marine clay, silt and silty clay that were deposited within the Champlain Sea basin. These deposits overlie relatively thin, commonly reworked glacial till and glaciofluvial deposits, that in turn overlie bedrock consisting of shales, dolostones and limestones.

Overburden materials tend to fill depressions in the bedrock surface in the area, and reach thicknesses of up to 20 metres to 60 metres. Approximately six kilometres to the east of the Site the overburden thins due to a north-northeast trending buried bedrock ridge. Glacial till deposits are present at surface over the ridge as shown on Figure 3-11 (Cross-Section D-D').

The Vars-Winchester buried esker (a buried deposit of sand and gravel) occurs a few kilometres east of the ridge, and roughly parallels the north-northeast trend of the buried bedrock ridge (Figure 3-11). The esker is about eight kilometres east of the Site and is separated from the Site by the bedrock ridge, and the surrounding thick clay deposits.

12.1.2 Hydrostratigraphy

The hydrostratigraphic units which underlie the Site were characterized through a series of geotechnical and hydrogeological investigations as described in Section 2.0. Based on these investigations, seven hydrostratigraphic units are identified as follows:

- **Surficial silty sand**: Silty sand was observed at surface in all but four of the borehole locations completed as part of the subsurface investigation at the Site. Where present on the Site, the sand was found to vary in thickness between 0.3 metres and 2.7 metres, with an average thickness of approximately one metre. An isopach map of this unit is presented on Figure 3-16 Panel A. Horizontal hydraulic conductivity of the surficial silty sand unit was found to vary between 9 x 10^{-8} m/sec to 2 x 10^{-5} m/sec, with a geometric mean value of 2.5 x 10^{-6} m/sec (Section 7.2.4). Residential wells in the area are dug wells, and draw water from this unit.

- **Weathered clay**: A thick and continuous silty clay unit was observed to underlie the surficial silty sand unit (or outcrop at surface where sand is absent). At most borehole locations, the upper portion of the silty clay was weathered. The weathered portion varies in thickness between 0.1 metres and 1.3 metres, with an average thickness of 0.43 metres. The thickness of the weathered clay unit was found to be inversely proportional to the thickness of the overlying surficial silty sand unit, with the weathered clay unit being thickest where clay is present at the surface.

- **Silty clay**: The total thickness of the silty clay unit (including the weathered clay) ranges from approximately 19 metres to 35 metres, with a minimum of about 25 metres below the Site (Figure 3-16, Panel B). As discussed above the upper 0.1 metres to 1.3 metres of this unit has been weathered. The silty clay unit was found to contain occasional silt and silty sand seams. The vertical hydraulic conductivity of this unit was found to range from 1.2 x 10^{-11} to 1.8 x 10^{-9} m/sec, with a geometric mean value of 1.0 x 10^{-9} m/sec based on the results of laboratory testing (Section 7.2.3). Given the low vertical hydraulic conductivity of this unit, it is interpreted to behave as an aquitard, with primarily vertical groundwater flow occurring through this unit, between the surficial silty sand, and the glacial till below. Given the relatively low hydraulic conductivity of this unit, groundwater flow volumes through the silty clay would be low. As discussed below, a thin but continuous layer of sand silt to silty sand, trace clay is present within the silty clay unit (referred to as the silty layer). For discussion purposes, the terms upper and lower are added as descriptors when referring to the silty clay above and below the silty layer, respectively. These terms are used for spatial reference only, and are not meant to imply a change in the hydraulic properties of the unit.

- **Silty layer**: A continuous but thin layer of silty soil was observed within the upper portion of the silty clay unit at all of the borehole locations at the Site. The thickness of this unit was found to vary from 0.1 metres to 0.6 metres with an average thickness of 0.3 metres (Figure 3-17, Panel A). This unit was typically found between three and four metres below the top of the clay unit (average depth of 3.95 metres below the top of the weathered clay unit). The horizontal hydraulic conductivity of this unit ranges from 3 x 10^{-8} m/sec to 3 x 10^{-6} m/sec, with a geometric mean value of 8 x 10^{-7} m/sec (Section 7.2.4). As the hydraulic conductivity of this layer is higher than the silty clay above and below, horizontal flow may occur through this layer; however, given the relatively small thickness of this layer, groundwater flow volumes in this unit would be low.

- **Glacial till:** The thickness of this unit was found to vary between two metres and nine metres in boreholes at the Site (Figure 3-17 Panel B). The horizontal hydraulic conductivity of this unit varies from 8 x 10^{-9} m/sec to 2 x 10^{-4} m/sec with a geometric mean value of 1.5 x 10^{-6} m/sec (Section 7.2.4). There are few drilled residential wells in the area; however, those that do exist take their water from the contact between the glacial till unit and the underlying bedrock. In general, this contact aquifer produces enough water for domestic supply; however, the water produced is generally not potable.

- **Queenston Formation**: Although not observed in boreholes at the Site, mapping of local geology indicates the presence of the Queenston shale as the upper bedrock unit to the south of the Site (see Section 3.1.1, Figure 3-6). Horizontal hydraulic conductivity of this unit ranges from 3.6 x 10^{-9} m/sec to 3.0 x 10^{-6} m/sec (Golder, 2013), with a geometric mean value of 5.5 x 10^{-7} m/sec.

- **Carlsbad Formation**: Bedrock observed in boreholes extended to bedrock at the Site generally consists of fresh, very thinly to thinly bedded, dark grey to black, interbedded shale, calcareous shale, shaley to argillaceous limestone and limestone bedrock of the Carlsbad Formation. This formation is inferred to be more than 150 metres thick below the Site (Figure 3-7). The horizontal hydraulic conductivity of the upper four to six metres of the Carlsbad bedrock varies from 2 x 10^{-8} m/sec to 2 x 10^{-5} m/sec, with a geometric mean value of 7 x 10^{-7} m/sec (Section 7.2.4).

A hydrostratigraphic model of the South Nation watershed (that includes the CRRRC Site) was developed by the GSC (Logan et al., 2009). This model defines the top surface elevation of eight hydrostratigraphic units based on the analysis of various data sources. The defined units include: recent deposits, organic deposits, basin sand, basin mud, glaciofluvial sediment, sandy silt till, sub-till sediment, and Paleozoic bedrock. These surfaces are generally consistent with the local cross-section shown on Figure 3-11. Locally, the surficial silty sand unit is discontinuous and is present in distinct areas to the north of Highway 417, to the southwest of the Site near the headwater of the Castor River, and in small areas overlying the bedrock ridge. Where present, the sands range in thickness from less than 0.1 metres to 15 metres. Locally, the thickness of the silty clay unit varies between 20 metres and 40 metres. This unit is thinner (i.e., less than 20 metres) where rivers and creeks (such as the Bear Brook Creek) have incised the clay, and is not present above the bedrock ridge to the east of the Site. The till and sub-till sediments form a unit that varies in thickness between 1 metre and 15 metres.

12.1.3 Groundwater Flow Directions and Hydraulic Gradients

Groundwater flow directions and hydraulic gradients observed at the Site are discussed in detail in Sections 7.2.1 and 7.2.2. Horizontal groundwater flow in the surficial silty sand, the silty layer, silty clay, glacial till and upper bedrock were observed to be towards the east/northeast direction. Local groundwater contours are shown on Figures 7-1 through 7-4. Average horizontal hydraulic gradients in the surficial silty sand, silty clay, glacial till, and upper bedrock are very low and range from 0.0006 to 0.0008 m/sec. The vertical hydraulic gradients at the Site are generally downwards.

Locally, the shallow groundwater flow in the overburden units is interpreted to be towards rivers, creeks, drains, and, where present, tile drainage systems (WESA, 2010). Surface water features in the area that may influence shallow groundwater flow include: Bear Brook Creek and Regimbald Municipal Drain to the north of the Site, the Castor River to the south of the Site, the Bear River and Rochon Municipal Drains to the east of the Site, and the Simpson Municipal Drain, which runs west to east through the Site. Deep regional bedrock groundwater flow is generally interpreted to be to the north or northeast towards the Ottawa River (WESA, 2010).

12.1.4 Effect of Clay Consolidation on Groundwater Flow

As discussed in Section 11.3 the additional stresses to the underlying soils imposed by the landfill can induce time-dependent drainage of porewater from the underlying soils, resulting in consolidation. The silty clay deposit underlying the Site is expected to experience consolidation and subsequent settlement. The following consolidation processes and effects may influence groundwater flow at the Site:

- During the period in which porewater is draining from the silty clay, there will be persistent excess porewater pressure in the silty clay. As a result of these excess porewater pressures, upward vertical hydraulic gradients may be generated. A plot of hydraulic head variations with depth under a load equivalent to 20 metres of waste is shown on Figure 12.1 for various times in the consolidation process.

These results are based on the results of the Settle-3D modelling described in Section 11.3. These schematics are shown considering observed vertical hydraulic gradients at the Site. These results suggest that consolidation of the silty clay unit may result in upward hydraulic gradients below the landfill that persist for between 25 and 50 years following the placement of the waste, creating a barrier to downward seepage during this period.

- The consolidation of the silty clay deposits will result in settlement of the overlying stratigraphic layers. This settlement is highest where the waste is thickest, and reaches zero at the toe of the berm. Due to this differential settlement, the stratigraphic layers will shift towards a bowl structure. This differential deformation will act as a structural trap to leachate generated at the Site.
- The reduction in volume of the clay with consolidation is associated with the realignment of clay minerals towards a more horizontal orientation, and a subsequent reduction in vertical hydraulic conductivity. It is assumed that this reduction may be by as much as one order of magnitude for the fully consolidated clay based on the results of oedometer consolidation testing completed as a component of this study (Section 6.3).

12.2 Three-Dimensional Numerical Groundwater Flow Model

A 3-D numerical groundwater flow model was constructed to provide a quantitative evaluation of hydraulic head drawdown, groundwater flow paths, groundwater seepage rates, and groundwater travel times resulting from the proposed development of the CRRRC Site. The groundwater flow model was developed using FEFLOW (Finite Element subsurface FLOW system) Version 6.1, WASY Ltd. (www.wasy.de). FEFLOW is capable of representing groundwater flow, contaminant mass transport and heat transfer using finite elements. The objective of this modelling study was to evaluate potential effects of the Site on groundwater quantity. Potential effects on groundwater quality are evaluated separately (see Section 12.3).

12.2.1 Model Construction and Grid Discretization

The model domain is bounded by the Bear River municipal drain in the west, Bear Brook Creek in the north, and the North Castor/Castor River in the south. The bedrock ridge was used to define the eastern boundary of the model domain. As discussed above, the ridge acts as a structural barrier for flow in the overburden to the east (towards the Vars-Winchester Esker). It is also noted that, as the ridge is a topographically high point in the area, it also acts as a recharge area. The modelled domain is shown on Figure 12-2.

The 3-D mesh was generated from a vertical extension of a two-dimensional (2-D) mesh to all hydrostratigraphic units. The 2-D mesh is made of 35,017 nodes forming 69,637 triangular finite elements. The 3-D mesh was generated by an extension of the 2-D mesh from the ground level to the base of the model domain while using the geodetic elevations of hydrostratigraphic unit contacts. The resulting mesh was subdivided into 17 layers (18 numerical slices) made of 630,306 nodes and forming 1,183,829 triangular prism shape finite elements for the predictive simulations.

The hydrostratigraphic layers, and surfaces used to define them are summarized as follows:

- **Layers 1 and 2:** These layers represent the surficial geology as shown on Figure 3-10. Borehole observations at the Site have shown that the surficial silty sand unit is present over a larger area than indicated by surficial mapping. As limited borehole observation data is available outside of the Site boundaries, this silty sand unit was extended to the east and west of the Site towards the Regimbald Municipal Drain, to provide a conservative representation of any potential connection between the drain and the Site. The top surface of Layer 1 was defined by local topographic and survey data. The bottom surface of Layer 2 was locally defined within the Site using borehole observations, and defined throughout the remainder of the model domain using the basin mud surface from the South Raisin Hydrostratigraphic model (Logan et al., 2009). The combined thickness of Layers 1 and 2 varies from 1 to 2 metres in the area of CRRRC site. The surficial silty sand unit is present in these layers only.

- **Layers 3 and 4:** These layers represent the weathered clay unit, with a uniform combined thickness of 0.5 metres. The properties of the till unit were assigned to these layers in the area where glacial till is present at the surface (i.e., where the clay unit pinches out).

- **Layers 5 and 6:** These layers represent the upper silty clay unit. The base of this layer is defined as the top of the silty layer. The combined thickness of these layers ranges from 1 metre to 5.7 metres within the Site boundaries, and was fixed at a uniform value of 3.45 metres elsewhere within the model domain. The properties of the till unit were assigned to these layers in the area where glacial till is present at the surface.

- **Layers 7 and 8:** These layers represent the silty layer. The combined thickness of these layers ranges from 0.1 metres to 0.6 metres within the Site boundaries, and was fixed at a uniform value of 0.3 metres elsewhere in the model domain. The properties of the till unit were assigned to these layers in the area where glacial till is present at the surface.

- **Layers 9 and 10:** These layers represent the lower silty clay unit, and are bounded on the top by the silty layer and on the bottom by the glacial till unit. The properties of the till unit were assigned to these layers in the area where glacial till unit is present at the surface.

- **Layers 11 and 12:** These layers represent the glacial till unit, which is assumed to be continuous throughout the model domain. The top surface of Layer 11 is defined on the Site using the borehole information described above, and defined elsewhere in the model using the glacial till and sub-till sediment surfaces from the South Raisin Hydrostratigraphic model (Logan et al., 2009). The combined thickness of these layers varies from 1 metre to 11.2 metres.

- **Layer 13 and 14:** These layers represent the Paleozoic bedrock units. The top surface Layer 13 was defined using the bedrock surface elevation discussed in Section 3.2.1. Layer 13 was assigned a uniform thickness of 50 metres, while Layer 14 was assigned a uniform thickness of 100 metres.

12.2.2 Boundary Conditions

The boundary conditions specified in the model are illustrated on Figure 12-3 and include the following:

- The eastern boundary of the model domain was assigned using a combination of no flow and specified head boundaries. A no flow boundary was assigned along the bedrock ridge to represent the water table mounding observed in the WESA (2010) study. At the northern and southern ends of the ridge, specified head boundaries were assigned along mapped surface water features. The interpreted boundary conditions are in agreement with the piezometric surfaces developed as a component of regional groundwater modelling completed by WESA (2010).
- Specified head boundaries were assigned to the main rivers, creeks and drains within the model domain. Assigned heads correspond to ground surface elevations.
- Seepage boundaries at the Simpson Drain and DD2.

Recharge was estimated through the calibration of the numerical model. Calibrated values are summarized in Table 12-1. These values represent between 0.5% and 2% of mean precipitation.

Table 12-1: Calibrated Recharge Rates

Surficial Unit	Recharge (mm/year)
Silty Sand	20
Weathered Clay	5
Glacial Till	15

12.2.3 Material Properties

The simulated hydraulic conductivity distribution for the various units is shown on Figure 12-4. The hydraulic parameters assigned to the various units are summarized in Table 12-2.

Table 12-2: Summary of Hydraulic Parameters Assigned in the Calibrated Numerical Model

Unit	Horizontal Hydraulic Conductivity (m/sec)	Anisotropy (K_H:K_v)	Specific Storage (m^{-1})	Specific Yield (-)
Surficial Silty Sand	2.0×10^{-5}	1:1	2.0×10^{-4}	0.2
Weathered Clay	1.0×10^{-7}	10:1	2.0×10^{-3}	0.05
Unweathered Clay	1.0×10^{-8}	10:1	2.0×10^{-3}	0.05
Silty Layer	8.0×10^{-7}	1:1	2.0×10^{-4}	0.1
Glacial Till	1.5×10^{-6}	1:1	2.0×10^{-4}	0.1
Queenston Shale Bedrock Formation	5.5×10^{-7}	1:1	3.0×10^{-6}	0.01
Carlsbad Bedrock Formation	7.0×10^{-7}	1:1	3.0×10^{-6}	0.01

Hydraulic conductivity values presented above were assigned based on hydraulic testing completed at the Site (Section 7.2.4), and calibration of the numerical model. Storage parameters were selected from literature values (Anderson and Woessner, 1992).

12.2.4 Model Calibration

The calibration of the groundwater flow model was evaluated by comparing the simulated steady-state groundwater elevations to measured groundwater elevations. The calibration dataset consisted of average groundwater elevations observed at the Site (between January and October 2013), and was supplemented using available data from the MOECC WWIS (MOE, 2013), and data from other Golder projects within the model domain.

As standard practice, a groundwater flow model is considered calibrated when the root mean square error (RMS) is within 5 to 10% of the total head variation over the domain (Anderson and Woessner, 1992). The RMS error for the calibrated model is 3.1 metres. With a total head variation of 25.8 metres over the domain, the calibrated RMS value slightly exceeds the suggested target.

The relationship between observed and simulated hydraulic head values is shown on Figure 12-5. This figure shows that the majority of the points fall along the line marking simulated hydraulic heads equal to observed hydraulic heads, indicating that the calibrated model properly simulates groundwater flow within the modelled domain.

Within the Site boundaries, the calibrated model replicates the observed groundwater flow directions, and hydraulic gradients in each of the hydrostratigraphic units. Simulated hydraulic heads are within 0.8 metres of the observed hydraulic heads at the Site, with an average residual of 0.2 metres. The hydraulic head residual for monitoring wells on the Site falls within the range of seasonal variability, indicating that the model is locally well calibrated.

12.2.5 Predictive Simulations

Predictive simulations of the post-development Site conditions were completed considering potential scenarios. Simulations were completed to represent steady-state conditions with an operating leachate collection system, and steady-state conditions following failure of the leachate collection system. Failure of the leachate collection system is not expected to occur until more than 100 years after the closure of the Site. Simulations were also completed to represent the steady-state conditions following the structural deformation of the stratigraphic layers resulting from consolidation of the silty clay unit. Consolidation was taken to be complete within 50 years following closure of the Site. Post-development conditions at the Site were represented by making the following changes to the calibrated model described above:

- Three additional slices were added to the model to represent the post-development infrastructure at the Site. The top slice represents the design surface of the landfill area and the perimeter berms. The second slice represents the interior side slopes of the perimeter berm, and the top of the drainage layer. The third slice was placed a distance of 0.6 metres below the second slice, representing the approximate thickness of the drainage layer. Within the Site boundaries, Slice 7 was adjusted to a distance of 0.25 metres below Slice 3 to represent the perimeter GCL hydraulic barrier to be constructed to provide cut-off for the perimeter berm fill, surficial sand and weathered clay. Where the fill area is not lined, Slice 7 was placed 0.5 metres below Slice 3 to represent the approximate thickness of the remaining surficial units underlying the leachate collection system. Slices 4, 5, and 6 are intermediate slices.
- The seepages boundaries representing the DD2 drain (location shown on Figure 2-2) within the landfill footprint were removed, and specified head boundaries were assigned to represent the leachate collection system at an elevation of 0.3 metres above the base of the drainage layer. Specified head boundaries

were assigned at 0.5 metres below the top of the perimeter berm to represent the planned ditch network at the edge of the berm. Seepage boundaries were assigned along the sideslopes and base of the waste and the berm.

- Recharge rates to the waste during operations and closure were assigned values of 289.6 and 269.6 millimetres per year, respectively, based on HELP model results (Section 12.3.4). Recharge on the berm was assigned a value of 5 millimetres per year. Recharge on the portion of the Site to the north of the Simpson Drain was assigned a value of 0 millimetres per year to represent the planned development in that area.

Material properties of the various post-development infrastructure components are summarized in Table 12-3.

Table 12-3: Summary of Hydraulic Parameters Assigned in the Post-development Numerical Model

Unit	Horizontal Hydraulic Conductivity (m/sec)	Anisotropy (K_H:K_v)	Specific Storage (m^{-1})	Specific Yield (-)
Waste (Operations)	1.0×10^{-5}	1:1	2.0×10^{-3}	0.1
Waste (Closure)	1.2×10^{-5}	1:1	2.0×10^{-3}	0.1
Drainage Layer	1.0×10^{-4}	1:1	2.0×10^{-4}	0.3
GCL Hydraulic Barrier	3.0×10^{-10}	1:1	2.0×10^{-3}	0.0001
Berm	1.0×10^{-7}	1:1	2.0×10^{-3}	0.05
Consolidated Weathered Clay	1.0×10^{-7}	100:1	2.0×10^{-3}	0.05
Consolidated Unweathered Clay	1.0×10^{-8}	100:1	2.0×10^{-3}	0.05

Note: Hydraulic conductivity of the waste is increased slightly at closure to represent the addition of a permeable cover

The hydraulic conductivity of the waste during the closure period is slightly higher than in operations to account for the addition of a permeable cover. The GCL hydraulic barrier will be approximately 0.95 centimetres thick with a hydraulic conductivity of approximately 1×10^{-11} m/sec. The hydraulic conductivity assigned for the GCL in the model is considered equivalent to the GCL hydraulic conductivity for the 0.25 metres thickness modelled. A cross-section showing the post-development hydrostratigraphic model layers is included on Figure 12-6.

The consolidation of the upper and lower silty clay units was represented in the model using the results of the settlement modelling discussed in Section 11.3. Consolidation affected only the clay units (Model Layers 8, 9, 12 and 13), while the overlying non-consolidated stratigraphic layers were translated downward by the same degree as the underlying layers. The settlement of the waste was not included in this analysis. The vertical hydraulic conductivity of the fully consolidated layers was decreased by one order of magnitude based on the results of oedometer consolidation testing completed as a component of this study (Section 6.3). A cross-section showing the post-consolidation model layers is shown on Figure 12-7. It is noted that this settlement representation is a simplified and steady state approximation of the consolidation process, and is only representative of structural changes once consolidation has been completed. The hydraulic effects of the consolidation process on excess porewater pressure development were not represented. As a result, the groundwater model presents a conservative approximation of the potential for groundwater seepage off-Site. As discussed in Section 12.1.4, during consolidation, excess porewater pressures will generate upward hydraulic gradients, resulting in a hydraulic barrier for downward vertical seepage from the landfill.

12.2.6 Results

The predictive model was used to estimate pseudo-steady state seepage rates and groundwater levels for the following scenarios:

- **Predictive Scenario (PS1):** Operating leachate collection system, pre-settlement, operational conditions;
- **Predictive Scenario (PS2):** Operating leachate collection system, post-settlement, closure conditions; and,
- **Predictive Scenario (PS3):** Failed leachate collection system, post-settlement, closure conditions.

Groundwater drawdown provides an indication of the extent to which the landfill could potentially affect off-Site groundwater quantity. Groundwater drawdown was calculated for each pre-failure scenario relative to the calibrated pre-development conditions. Groundwater drawdown will be most significant while the leachate collection system is in operation; as such, scenarios PS1 and PS2 represent the greatest potential for groundwater lowering. Figure 12-8 and Figure 12-9 show the drawdown iso-contours at steady state for PS1 and PS2, respectively. As shown on the figures, the simulated drawdown does not extend beyond the property boundary for any of the scenarios. Therefore the proposed Site development is not predicted to have any measurable impact on groundwater quantity (and off-Site dug well supply) outside of the property boundary. It is noted that the drawdown to the north of the Simpson Drain, within the property boundary, is due to the reduction in recharge resulting from the development of that portion of the Site.

As discussed in Section 12.3.7, failure of the leachate collection system would result in mounding of groundwater within the landfill component. The effect of this mounding on groundwater elevations is shown on Figure 12-10 for PS3. The predicted effect of the Site on groundwater levels post-failure does not extend beyond the property boundary.

Hydraulic head contours for the silty layer and the glacial till / bedrock contact are shown on Figure 12-11 for the PS3 scenario. These results show that groundwater seepage in the silty layer will flow radially away from the Site until it enters the local flow regime. Groundwater seepage in the glacial till / bedrock contact will be as under existing pre-development conditions and generally flow towards the northeast.

The travel time for particles released under steady-state conditions following failure of the leachate collection system, and representative of the first arrival of a conservative tracer at the glacial till/bedrock contact is on the order of 500 years.

12.3 Assessment of Long-Term Groundwater Impacts

12.3.1 Regulatory Objectives

Modelling of long-term groundwater quality impacts for new or expanding landfill sites is required under O.Reg. 232/98 (MOE, 1998a) to demonstrate that the proposed design will meet the requirements of MOECC Guideline B-7 (MOE, 1994b).

The Reasonable Use Guideline B-7 (MOE, 1994b) establishes a quantitative benchmark for protecting off-Site groundwater quality for drinking water purposes. The Reasonable Use Guideline makes the following statement regarding groundwater impact at the landfill property boundary:

> *"In the case of drinking water, the quality must not be degraded by an amount in excess of 50% of the difference between background and the Ontario Drinking Water Objectives for non-health related parameters and in excess of 25% of the difference between background and the Ontario Drinking Water Objectives for health related parameters. Background is considered to be the quality of the groundwater prior to any man-made contamination."*

In terms of any engineered facilities the *Landfill Standards: A Guideline on the Regulatory and Approval Requirements for New or Expanding Landfilling Sites* (Landfill Standards) (MOE, 1998b, revised January 2012), a document which provides help in understanding O.Reg. 232/98, makes the following statement regarding the basis for evaluation of the acceptability of proposed engineered facilities at landfills:

> *"An engineered facility which is to be constructed at a landfilling site for purposes of controlling leachate, groundwater, surface water or landfill gas should be designed such that: the service life of the engineered facility exceeds the period of time during which contaminants may be generated by the site and need to be controlled by the engineered facility to prevent an unacceptable impact; or the engineered facility can be replaced, or an alternative engineered facility can be constructed, as necessary to enable the combined service lives of the engineered facilities to exceed the period of time during which contaminants may be generated by the site and need to be controlled by the engineered facility to prevent an unacceptable impact."*

12.3.2 Geological/Hydrogeological Conditions Modelled Beneath the Landfill

The geological/hydrogeological conditions modelled are based on the stratigraphic Section E-E' shown on Figure 3-14. As described in Section 10.8, the landfill component of the CRRRC will be surrounded by a constructed hydraulic barrier consisting of a geosynthetic clay liner (GCL) keyed into the silty clay which will cut off the horizontal flow to the surficial silty sand and perimeter berm fill. While the silty layer does not convey a substantial amount of water, it was conservatively used to represent the groundwater resource that is the most susceptible to landfill leachate impacts.

For the purpose of the contaminant transport modelling, Section E-E' was simplified as shown on Figure 12-14 with two distinct silty clay layers of uniform thickness separated by a 0.3 metre silty layer. The depth of the base of the landfill varies from 1.5 metres to 2.5 metres below the original ground surface. As a result of the difference in base elevation, in some areas below the landfill there will be pockets of the surficial silty sand. The silty sand below the landfill will be cut-off from the surrounding surficial silty sand with a GCL hydraulic barrier as described in Section 10.8. To be conservative, the thickness of the surficial silty sand was taken to be 0.5 metres everywhere below the landfill. For the purposes of the contaminant transport model, the surficial silty sand and upper silty clay were modelled as one layer (with a weighted hydraulic conductivity as discussed later). The silty layer was modelled as a horizontal "sink" at the top of the lower silty clay. During operation of the landfill the average thickness of the silty clay deposits below the landfill are 3.3 metres and 23.3 metres for the silty clay above the silty layer and below the silty layer, respectively. The top 3 metres of the glacial till deposit (assumed mixing zone of landfill contaminants within the glacial till deposit) underlies the silty clay in the conditions modelled.

As discussed in Section 11.3, the silty clay beneath the landfill will settle over time. The amount of settlement depends on the length of loading time as well as the thickness of the waste in the landfill. An average landfill waste thickness of 12 metres was used (based on a volume of 10.1 million m^3 and a footprint area of 84 hectares). The elevations of the base of the landfill and the silty layer were adjusted over time using the upper bound predicted settlement for the average waste thickness as shown on Figure 12-14. The following assumptions were made for the model related to settlement:

- The surficial silty sand below the landfill will be an average of 0.5 metres thick;
- The silty layer will remain 0.3 metres thick;
- The top of the glacial till will remain at the same elevation; and,
- The average thickness of the upper silty clay below the landfill after 100 years of settlement was conservatively used to represent the thickness of the upper silty clay in the model from year 0.

The soil types, layer thicknesses and water levels shown on Figure 12-14 are representative of the conditions throughout the proposed landfill area.

Modelling input values for hydraulic conductivity (K), porosity (n), dry density and fraction organic carbon (foc) content of each soil layer are presented on Figure 12-14. The vertical hydraulic conductivity values shown for the surficial silty sand and glacial till were conservatively assumed to be equal to the geometric mean horizontal hydraulic conductivity determined from in-situ rising head tests (refer to Table 7-3). The results of the permeability testing completed on a sample from the upper silty clay (refer to Table 7-2) was used to represent the existing hydraulic conductivity for the upper silty clay. The average results of the permeability tests completed on two samples from the lower silty clay (Table 7-2) were used to represent the existing hydraulic conductivity of the lower silty clay. To account for the compression of the silty clay layers, the hydraulic conductivities were decreased by an order of magnitude considering settlement at 50 years from the start of filling. For the contaminant model, a weighted hydraulic conductivity of the surficial silty sand and upper silty clay were used for the upper silty clay layer. The horizontal hydraulic gradient in the silty layer and the glacial till was taken as 0.0009 (slightly high than interpreted from the groundwater data for the silty layer).

The average porosity (n) of 0.54 for the silty clay was calculated using the final void ratios (e) measured on oedometer test samples from boreholes completed south of the Simpson Drain (i.e., in the area of the landfill). The formula used to calculate the porosity is as follows:

$$n = e/(1 + e)$$

The porosity of the glacial till was assumed as a typical value of 0.35.

The fraction organic carbon content of the silty clay was calculated to be 0.145%, which is the average of two fraction organic carbon analyses completed on a sample obtained from 2.1 to 2.7 metres below ground from borehole 12-3-3. Fraction organic carbon was also measured in the lower silty clay at 0.40% and 0.36% at borehole 12-1-3 and borehole BH12-02-3, respectively. To be conservative, the lower fraction organic carbon value of 0.145% was applied to both the upper and lower silty clay.

Based on groundwater level monitoring carried out, the primary groundwater flow path within the silty layer is interpreted to be consistently to the east. A horizontal hydraulic gradient of 0.0009 was used for the silty layer. The contaminant dispersivity for this flow path was taken as 0.3 metres. The distance from the downgradient (east) side of the landfill to the east property boundary is about 125 metres.

12.3.3 Landfill Modelling Approach

The contaminant transport modelling for the proposed landfill was carried out using POLLUTE (Rowe, et al., 1994). POLLUTE is a one-dimensional, analytical contaminant transport model, which can account for contaminant migration from a landfill situated on a multi-layered soil deposit. The model predicts concentrations in the aquifer unit at the down-gradient edge of a landfill.

The contaminant transport processes accounted for by the model include: molecular diffusion, mechanical dispersion, advection, adsorption onto soil solids and bio-chemical decay in the landfill and underlying soil layers. For the hydrogeological conditions at the CRRRC landfill, advection/dispersion and bio-chemical decay are the primary transport processes in the sandy silt and till layers, whereas diffusion is the primary transport process in the upper and lower silty clay layers, with the advection, adsorption and bio-chemical decay playing lesser roles.

The boundary condition used for contaminant source concentrations in the landfill is that of a depleting contaminant concentration with time from an initial representative peak value that occurs at the closure of the landfill component. The depletion in concentration once the area being landfilled is completed is due to bio-chemical decay and wash-out by moisture infiltration/percolation through the waste mass. The rate of concentration decrease with time is a function of the bio-chemical decay half-life, the representative peak leachate concentration, the contaminant mass inventory in the landfill and the moisture infiltration rate through the landfill cover. POLLUTE does not account for volatilization of VOCs and, as such, is conservative in this respect.

The model and approach used to evaluate groundwater quality impacts was extended for 1,000 years beyond the time that waste filling was assumed to commence.

12.3.4 Landfill Leachate Generation Rates

The long-term (steady-state) leachate generation rate for the landfill was calculated using the Hydrologic Evaluation of Landfill Performance (HELP) Model, assuming a landfill cover system consisting of a 0.6 metre thick layer of imported sandy silt to silty sand (or similar material) overlain by a 0.15 metre thick layer of soil capable of sustaining vegetation. The average annual infiltration rate through daily/intermediate cover was also evaluated using the HELP Model. The HELP model is a quasi-two dimensional hydrologic model designed by the U.S. Army Corps of Engineers for the U.S. EPA and is widely accepted for prediction of landfill surface run-off, evapotranspiration, leachate collection and leakage. The HELP model method of solution, assumptions and limitations can be found in the model documentation (Schroeder et al., 1994).

The climatological data used in the HELP Model were synthetically generated using mean monthly precipitation, wind speed and temperature data for the Ottawa MacDonald Cartier International Airport (Environment Canada, 2010) and precipitation / temperature variability coefficients for Syracuse, New York (Note: Syracuse data are included in the HELP Model data base). Values used for the key input parameters for the soil cover and refuse are summarized in Table 12-4.

a) Layer Data

Table 12-4: Input Parameters for Modelling Leachate Generation Rate Using HELP Model

Layer	Thickness (metres)	Total Porosity (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)
Vegetated Soil	0.15	0.437*	1.7 x 10^{-3*}
Cover Soil	0.6	0.437*	1.7 x 10^{-3*}
Refuse	12	0.168*	1.0 x 10^{-3}*

Note: * HELP Model default value for material type

b) General Data

Average Annual Total Precipitation = 993.5 mm/year (based on 1971 to 2000 Climate Normals for the MacDonald Cartier Ottawa International Airport)

Surface Slope of Final Cover = 5%

SCS Runoff Curve Number = 56 (based on sandy silt soil with a fair stand of grass)

Evaporative Zone Depth for Final Cover = 50 cm

Leaf Area Index = 2.0

The long-term (steady-state) average annual infiltration rate through daily/intermediate cover as predicted by the HELP model is 289.5 millimetres per year. Assuming a landfill final cover system comprised of silty sand or sandy silt soil final cover, the resulting long-term (steady-state) average leachate generation rate is 269.5 millimetres per year.

12.3.5 Landfill Key Contaminants and Associated Transport Parameters

In accordance with O.Reg. 232/98 (MOE, 1998a), the key leachate contaminants modelled for municipal solid waste to address long-term compliance with MOECC Guideline B-7 (MOE, 1994b) are: benzene, cadmium, chloride, lead, 1,4-dichlorobenzene, dichloromethane, toluene and vinyl chloride. Although it is not proposed that the CRRRC receive residential waste[1], and much of the organic component of the waste/residual stream should be able to be diverted from landfill (thus reducing some parameter concentrations in the leachate), utilizing these leachate contaminants and their proposed source concentrations is a conservative approach to impact assessment. In addition to the key leachate contaminants associated with municipal solid waste, boron was also used in consultation with the MOECC based on boron being a typical leachate indicator for IC&I waste.

Modelling input parameters required for each key landfill leachate contaminant are the representative peak leachate source concentration, mass inventory in the landfill (i.e., contaminant mass as a proportion of total mass of waste), half-life in the groundwater flow system, soil diffusion coefficient and soil adsorption coefficient. As shown on Table 12-5, the input for representative peak leachate source concentration, mass inventory and half-life are conservatively the same as the values recommended in Table 1 of O.Reg. 232/98, which are based on historical leachate quality monitoring for a number of municipal solid waste landfill sites in Ontario. Again, as

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[1] Recyclables from multi-residential developments will be received at the CRRRC if available.

the CRRRC will not receive municipal solid waste and will be incorporating a significant organics processing operation, use of these default values likely overstates actual source concentrations. The peak leachate source concentration for the IC&I waste key contaminant, boron, was obtained from peak leachate concentrations in a landfill accepting similar waste to the CRRRC landfill, while the mass inventory and half-life values were assumed based on literature values. The soil adsorption coefficients for the organic contaminants were calculated using literature values for soil/organic carbon partition coefficient (i.e., K_{oc}) and a laboratory fraction organic carbon (foc) for the upper silty clay deposit, as outlined in Table 12-5. Soil adsorption coefficients for the metals (i.e., boron, cadmium and lead) were assumed based on literature values for similar soil types.

The source concentrations of the key contaminants were generally increased to the representative peak leachate source concentration during the time that the landfill is being filled and then allowed to deplete. The background groundwater quality of the silty layer was obtained for all parameters from the median of two groundwater sampling events from seven monitoring wells on the Site.

Table 12-5: Key Contaminants and Associated Soil Transport Parameters – Silty Layer

Key Contaminant	Representative Peak Leachate Source Concentration [1] (mg/L)	Mass Proportion of Total (Wet) Mass of Waste [1] (mg/kg)	Half-Life (years)	Soil Adsorption Coefficient (mL/g)	Soil Diffusion Coefficient [6] (m^2/year)	Background Concentration [8] (mg/L)	Ontario Drinking Water Quality Objective (mg/L)
Chloride	1,500	1,800	Infinite[1]	0	0.019	890	250 (A)
Boron	17 [2]	20.4 [3]	Infinite	1 [7]	0.019	0.225	5 (H)
Cadmium	0.05	0.035	Infinite[1]	35 [5]	0.019	0.00005	0.005 (H)
Lead	0.6	0.42	Infinite[1]	1000 [5]	0.019	0.00025	0.01 (H)
Benzene	0.02	0.014	25[1]	1.250[4]	0.019	0.0001	0.005 (H)
1,4-Dichlorobenzene	0.01	0.007	50[1]	4.06[4]	0.019	0.00015	0.005 (H)
Dichloromethane	3.3	2.3	10[1]	0.5[4]	0.019	0.0005	0.05 (H)
Toluene	1	0.7	15[1]	2.828[4]	0.019	0.0003	0.024 (A)
Vinyl Chloride	0.055	0.039	25[1]	0.544[4]	0.019	0.0002	0.002 (H)

Notes:

[1] Values taken from Table 1 of O.Reg. 232/98 for municipal solid waste, except where stated.
[2] Based on maximum boron concentration in leachate recorded from a landfill that receives a similar waste type to the CRRRC landfill.
[3] Mass proportion directly related to chloride mass proportion divided by the chloride peak and multiplied by the peak of the parameter of interest (Rowe et. al., 1994a).
[4] Based on a fraction organic carbon content (foc) of 0.145% for the upper silty clay deposit and soil/organic carbon partition coefficients (Koc) of 862 mL/g for benzene, 345 mL/g for dichloromethane, 375 mL/g for vinyl chloride, 1,950 mL/g for toluene and 2,800 mL/g for 1,4-dichlorobenzene (Ref. Rowe et.al., 1994a).
[5] Rowe et.al., 1994a
[6] Assumed diffusion coefficient based on literature values for similar soils.
[7] Battelle Memorial Institute, 1989.
[8] Background based on median of groundwater concentrations in the silty layer within the clay deposit measured between January and July 2013.
(A) Denotes aesthetic drinking water objective
(H) Denotes health related drinking water objective

12.3.6 Service Life of Landfill Leachate Control System Components

The service life of the granular drainage layer is defined as the time at which the pores between the stone particles become clogged with bacteria and chemical precipitates (mainly calcium carbonate) to the extent that leachate can no longer be effectively collected, resulting in the development of a leachate mound above the base of the landfill.

As described in Section 10.8, a granular drainage blanket will be constructed below the waste and, together with a piping system, will convey the leachate to sumps where it will be removed from the landfill for treatment. It is proposed that the design for the granular drainage layer meet the requirements of Schedule 1 provided in O.Reg. 232/98. Based on this regulation, the service life of a leachate collection system that meets the requirements in Schedule 1 can be taken as 100 years, starting from either year 10 or the mid-point of the landfilling period, whichever is less.

The proposed sideslope liner system at the CRRRC landfill incorporates a GCL hydraulic barrier to prevent leachate from entering the surficial silty sand/weathered crust zone or overlying perimeter berm fill. This role of the GCL requires that its hydraulic conductivity remain very low, at values less than 3×10^{-10} m/s.

For a GCL that is properly installed in accordance with the manufacturer's procedures, the primary mechanisms that may limit its service life as a hydraulic barrier in a waste containment facility are cation exchange reactions and clay mineral breakdown on exposure to leachate. No natural weathering/breakdown of the bentonite clay component is expected as bentonite is already at the end-point of the soil weathering cycle.

Cation exchange reactions involve replacement of monovalent sodium ions adsorbed on the negatively charged bentonite clay particle surfaces with divalent calcium ions from the water / leachate that is in contact with the GCL. This in turn produces a more flocculated orientation of the clay minerals with larger interstitial pore spaces. The larger pore spaces increase the hydraulic conductivity of the GCL. With little or no surcharge on the GCL (e.g., <10 kPa), the increase in hydraulic conductivity can be more than one order of magnitude (Bishop, 1995). Egloffstein (2001) indicates that a minimum effective stress of 15 kPa (and preferably 20 kPa) is required for self-healing of the GCL clay fabric against cation exchange reactions. For the proposed CRRRC landfill, the estimated effective confining stresses acting on the sideslope GCL are larger than 20 kPa, with values of approximately 75 kPa at mid-slope and 105 kPa at the toe of slope. Therefore, based on the above results, self-healing of the sideslope GCL is expected to limit the potential increase in hydraulic conductivity such that the GCL will continue to perform adequately as a hydraulic barrier.

The mechanism of breakdown of the bentonite clay mineral on exposure to leachate is relevant only for high pH leachate (e.g., pH=12) and involves dissolution of silicon and aluminum, which are the primary elements forming the bentonite clay mineral structure. For the CRRRC landfill, the leachate pH is expected to be in the 5.2 to 8.0 range. At this pH range, silicon and aluminum solubility is very low and dissolution from the bentonite clay is expected to be insignificant.

In addition, the design of the base grades and leachate collection system for the proposed CRRRC landfill will direct the leachate away from the perimeter of the landfill and towards the manholes in the central portion for removal to treatment. As such, the leachate will not remain in sustained contact with the perimeter GCL.

The service life of the sideslope GCL as a hydraulic barrier around the perimeter of the proposed CRRRC landfill is expected to be comparable to the 1,000 year service life reported for a compacted clay liner in O. Reg. 232/98.

12.3.7 Landfill Leachate Mound Height

The average leachate head above the base of the landfill, which is underlain by the thick low permeability clay deposit that serves as a natural liner, was assumed to remain constant at 0.3 metres up to the point at which the leachate drainage layer fails. After leachate drainage layer failure, a leachate mound then begins to develop in these areas.

The average leachate mound height relative to perimeter ground surface elevation (h) after failure of the leachate collection system was calculated iteratively using the Harr Equation. An example is provided below.

$$\bar{h} = 0.393 \mathrm{x} L \mathrm{x} \sqrt{\frac{q_{net}}{k_{waste}}}$$

Where:

$\bar{h}$ = average leachate mound height (m) relative to perimeter ground surface elevation

L = minimum dimension of the landfill (perpendicular to the direction of groundwater flow)

= 350 metres

k_{waste} = hydraulic conductivity of the waste at the bottom of the landfill

= 315 m/year

q_{net} = portion of the cover infiltration rate (q_{inf}) contributing to the development of a leachate mound

= $q_{inf} – v_a$

q_{inf} = 0.2695 m/year

The Darcy flux (v_a) after failure of the leachate collection system was obtained from the 3-D groundwater flow modelling discussed in Section 12.2 of this report.

The calculation considers leachate drainage by seepage into the underlying soil layers and by outward seepage along the toe of the landfill at the perimeter berm (where the mound is higher than perimeter berm elevation).

The calculated average mound height was 4.0 metres (elevation 83.9 m ASL) above the top of the perimeter berm.

12.3.8 Vertical Leakage Rates

Table 12-6: Average Darcy Fluxes

Time (years)	Average Leachate Head on Silty Clay	Average Vertical Darcy Flux Between the Landfill and Upper Silty Clay, Va_1	Average Horizontal Darcy Flux in the Silty Layer [1]	Average Vertical Darcy Flux Through Lower Silty Clay, Va_2	Average Horizontal Darcy Flux in Glacial Till, Vb
0 – 20	0.3 metres	3 x 10^{-3} m/year ↑	0 m/year [4]	1.3 x 10^{-4} m/year ↓	0.11 m/year
20 – 30	0.3 metres	3 x 10^{-3} m/year ↑	0 m/year [4]	1.3 x 10^{-4} m/year ↓	0.11 m/year
30 – 70	0.3 metres	1.5 x 10^{-2} m/year ↑	0 m/year [4]	1.4 x 10^{-4} m/year ↓	0.12 m/year
70 – 100	0.3 metres	2 x 10^{-2} m/year ↑	0 m/year [4]	1.5 x 10^{-4} m/year ↓	0.115 m/year
100 – 104	3.7 metres	1.5 x 10^{-2} m/year ↑	0 m/year [4]	6 x 10^{-4} m/year ↓	0.28 m/year
104 – 108	7.0 metres	9 x 10^{-3} m/year ↑	0 m/year [4]	1 x 10^{-3} m/year ↓	0.45 m/year
108 – 112	10.4 metres	4 x 10^{-3} m/year ↑	0 m/year [4]	1.5 x 10^{-3} m/year ↓	0.61 m/year
112 – 1,112	13.7 metres	1.93 x 10^{-3} m/year ↓[3]	0.2 m/year [2]	2 x 10^{-3} m/year ↓ [2]	0.78 m/year

Notes:

[1] The horizontal Darcy flux was set to 0 m/year while the average vertical Darcy flux through the upper silty clay is upwards.

[2] Predicted from groundwater flow modelling discussed in Section 12.2 of this report.

[3] Calculated by continuity of flow with the average rate of removal through the 0.3 metre silty layer and the average vertical Darcy Flux through the lower silty clay over the 1,160 metre length of the landfill in the direction of groundwater flow.

[4] Horizontal Darcy Flux is not applicable due to upward flux between the landfill and upper silty clay and is set to 0 m/year for modelling purposes.

The hydraulic effects of the consolidation process on excess porewater pressure development were not represented. As a result, the vertical fluxes provided in the Table 12-6 above present a conservative approximation.

12.3.9 Results of Contaminant Transport Modelling

The results of the hydrogeologic/contaminant transport modelling are described below. An example of the POLLUTE output file is provided in Appendix R. Figure 12-15 shows the predicted key leachate contaminant parameter concentration variations with time at the downgradient edge of the landfill.

The results of the modelling for all key landfill leachate contaminant parameters are summarized in Table 12-7 and indicate essentially zero predicted impact on the silty layer at the downgradient edge of the landfill. For all parameters, the Reasonable Use Criteria for the silty layer (indicated in Table 12-7) are satisfied, noting that chloride naturally exceeds the ODWQS for chloride.

The negligible predicted impact for the organic contaminants (i.e., benzene, 1,4-dichlorobenzene, dichloromethane, toluene and vinyl chloride) on the silty layer relates primarily to biodegradation, mass removal through leachate collection and the very slow (diffusion controlled) rate of transport into the underlying silty clay deposit.

For boron, chloride, lead and cadmium, the negligible impact is due to the same processes noted above except that biodegradation does not apply for these parameters.

Table 12-7: Predicted Concentrations of Key Leachate Contaminants in the Silty Layer from the CRRRC Landfill

Contaminant	Background Median Concentration in Silty Layer (mg/L)[1]	Ontario Drinking Water Quality Standards [2] (mg/L)	Reasonable Use Criteria [3] (mg/L)	Predicted Peak Concentration* (mg/L)	Predicted Peak Plus Background Concentration* (mg/L)	Time of Peak Concentration** (years)
Boron	0.225	5 (H)	1.42	0.166	0.39	272
Chloride	890	250 (A)	N/A	16	906	272
Cadmium	0.00005	0.005 (H)	0.001	0.00004	0.00009	>1000
Lead	0.00025	0.01 (H)	0.003	0	0.00025	>1000
Benzene	0.0001	0.005 (H)	0.001	0	0.0001	162
1,4-Dichlorobenzene	0.00015	0.005 (H)	0.001	0	0.00015	272
Dichloromethane	0.0005	0.05 (H)	0.01	0	0.0005	122
Toluene	0.0003	0.024 (A)	0.01	0	0.0003	172
Vinyl Chloride	0.0002	0.002 (H)	0.0007	0	0.0002	142

Notes:

(H) Health-related objective.
(A) Aesthetic objective.
N/A Reasonable Use concentration cannot be calculated since the background concentration exceeds the ODWQS.

[1] Based on the median results of groundwater samples taken from groundwater monitoring wells BH12-1-5B, BH12-2-5B, BH12-3-5B, BH12-4-5B, BH13-5-5, BH13-6-5B and BH13-7-4-2 between January and July 2013.

[2] Ref. Ontario Drinking Water Quality Standards (MOE, 2003).

[3] Reasonable Use Criteria = Background Concentration + X (ODWQS Criteria - Background Concentration):
where X = 0.25 for health related drinking water parameters
= 0.50 for aesthetic related drinking water parameters

* Based on a 1,000 year contaminant transport modelling time frame, has been added to the background concentration.

** Relative to year 10 of the landfilling period.

12.3.10 Landfill Contaminating Lifespan

The contaminating lifespan for the proposed landfill component of the CRRRC corresponds to the time at which contaminant concentrations in the landfill have decreased to the extent that the landfill would no longer require the engineered system components to protect off-Site groundwater quality, but can rely on the natural containment provided by the silty clay deposit to do so.

To ensure protection of off-Site groundwater and compliance with MOECC requirements, the design of the proposed CRRRC landfill component relies primarily on: 1) the perimeter GCL hydraulic barrier and operation of the leachate collection system for protection of groundwater quality within the on-Site surficial silty sand layer, and 2) the natural silty clay deposit augmented by the leachate collection system for protection of the groundwater within the on-Site silty layer located several metres below the base of the landfill.

In addition to the above modelling, sensitivity analyses were carried out to assess a number of scenarios related to the potential impact to the subsurface silty layer: all contaminants going to the silty layer; settlement of the underlying clay deposit; and early failure of the leachate collection system beneath the landfill. The sensitivity analyses are reported in Section 12.3.10.1. Under these scenarios, the Site is still predicted to remain in compliance with the Reasonable Use Criteria (MOE, 1994b). All of these analyses show that should the leachate collection system fail after 20 years beyond the mid-point of landfilling or 20 years beyond year 10 after filling commenced, the thickness and low hydraulic conductivity of the natural silty clay deposit would provide the required off-Site groundwater protection. Nevertheless, the leachate collection system while functioning still helps ensure the protection of groundwater within the surficial silty sand layer by reducing leachate mounding on the GCL barrier. Monitoring of leachate levels within the landfill will be ongoing during operations and post-closure, and determine the need for contingency measures to prevent seeps and breakouts that could potentially impact surface water.

As described in Section 10.8, the design of the leachate collection system is such that leachate movement is towards sumps in the centre portion of the landfill, away from the perimeter of the landfill. The consolidation of the clay under the weight of the landfill will enhance this flow even more over time. As such, a significant mound of leachate will have to build up within the landfill before there is a leachate head against the perimeter of the landfill and the GCL, which would be the condition required for leachate to potentially diffuse through the GCL hydraulic barrier and into the surficial silty sand layer. Should leachate diffusion through the GCL barrier occur it would be detected by the monitoring program and there are a number of contingency measures available to ensure protection of off-Site groundwater in the surficial silty sand layer in such circumstances as described in Section 14.1.

In conclusion, the assumed service lives of both the leachate collection system (100 years) and the GCL (greater than 1,000 years) exceed the contaminating lifespan of the landfill.

12.3.10.1 Sensitivity Analyses

A sensitivity analysis involves changing a particular parameter to determine what effect it has on contaminant impact. Within the POLLUTE model and solutions, numerous input values are required. These input values were based on the Landfill Standards' recommendations, site specific data and literature values. In all instances where multiple values were available, best and typically conservative estimates were used.

In general, when values are provided by the Landfill Standards these values are used unless there are Site-specific data that would be more appropriate. Sensitivity analysis is not generally conducted on MOECC-provided input parameters. Some parameters, whether from literature or site-specific data, have a limited range or are known to have a limited effect on the output of results from the various models and solutions. However, it is useful to conduct sensitivity analyses on some parameters that may have a wider range and/or are known to have an impact on model results. The sensitivity study was undertaken using the parameter boron. Boron is the most sensitive parameter for the Site because it has no decay, has the smallest adsorption coefficient and is not naturally occurring in high concentrations. The sensitivity analyses conducted for the proposed landfill component of the CRRRC are discussed below.

12.3.10.2 All Contaminants Going to the Silty Layer

The contaminant transport model considers that some of the leachate will continue downward through the lower silty clay towards the glacial till. This reduces somewhat the concentration of the key contaminant in the silty layer. A sensitivity analysis was run in which it was assumed that the silty layer was able to take all of the predicted downward groundwater flow in the upper silty clay below the landfill. For this scenario, the concentration of boron at the downgradient edge of the landfill was 0.7 milligrams per Litre (mg/L) compared to 0.16 mg/L when some groundwater flow into the lower silty clay was modelled. The peak boron concentration of 0.7 mg/L added to the background boron concentration is 0.9 mg/L, roughly 60% of the Reasonable Use Criteria of 1.4 mg/L. Therefore, the sensitivity analysis results indicate that even with all of the groundwater flow going to the silty layer (which is physically not possible), the Site is still predicted to remain in compliance with the Reasonable Use Criteria.

12.3.10.3 Settlement

The geotechnical analysis at the Site indicates that significant clay consolidation can be expected beneath the landfill, with the largest settlement at the centre of the landfill. The contaminant transport model accounted for this predicted settlement, which also results in an increase in flux into the landfill. A sensitivity analysis was run on contaminant impact to the silty layer assuming no settlement beneath the landfill. The clay was not consolidated and the hydraulic conductivity of the silty clay was not reduced by an order of magnitude. In addition, this sensitivity analysis was combined with the conservative assumption analyzed in the previous section with all of the flow going to the silty layer. Due to the increased clay thickness and hydraulic conductivity, it was also necessary to re-calculate the Darcy fluxes. The peak concentration of boron in the silty layer at the downgradient edge of the landfill is predicted to be 0.45 mg/L compared to 0.16 mg/L when settlement was modelled. The peak boron concentration of 0.45 mg/L added to the background boron concentration is 0.67 mg/L, less than half of the Reasonable Use Criteria of 1.4 mg/L. The sensitivity results indicate that without the settlement and the associated increased flux into the landfill, the Site is still expected to remain in compliance with the Reasonable Use Criteria.

12.3.10.4 Early Failure of the Leachate Collection System Beneath the Waste

The leachate collection system beneath the waste has been designed with mechanisms to accommodate the large settlements expected at the Site. The design of the leachate collection system will have slip couplings on the leachate collection pipe joints to accommodate pipe movement when settlement occurs. Also, the sumps are located in areas of the greatest thickness of waste, which is where the greatest settlement is predicted to occur. As such, the base slopes of the granular blanket and the pipes will increase over time towards the sumps. Nevertheless, the implications of a failure of the leachate collection system beneath the waste sooner than 100 years from the start of the model was considered. The sensitivity study was again undertaken using the parameter boron.

Results of the sensitivity analyses are provided in Table 12-8 as follows:

Table 12-8: Early Failure of Leachate Collection System

Time of Leachate Collection System Failure (years)	Predicted Peak Concentration of Boron (mg/L)	Predicted Peak Concentration of Boron with Background Concentration[1] (mg/L)	Reasonable Use Criteria[2] (mg/L)
100	0.166	0.39	1.42
30	0.777	1.002	1.42
20	0.865	1.090	1.42

Notes:

[1] Background concentration based on the median results of groundwater samples taken from groundwater monitoring wells BH12-1-5B, BH12-2-5B, BH12-3-5B, BH12-4-5B, BH13-5-5, BH13-6-5B and BH13-7-4-2 (completed in the silty layer) between January and July 2013.

[2] Reasonable Use Criteria = Background Concentration + X (ODWQS Criteria - Background Concentration):
where X = 0.25 for health-related drinking water parameters
= 0.50 for aesthetic-related drinking water parameters

The expected boron background concentration in the silty layer is 0.225 mg/L. When the leachate collection system functions for 100 years, the predicted peak concentration of boron in the silty layer (after addition of the background concentration) is 0.39 mg/L. Even if it is assumed that the leachate collection system fails after 20 years, the impact to the silty layer is 1.09 mg/L at the downgradient edge of the landfill footprint, less than the Reasonable Use Criteria of 1.42 mg/L. This sensitivity analysis demonstrates that even with significantly earlier failure of the leachate collection system, the Site is still expected to remain in compliance with the Reasonable Use Criteria.

12.4 Summary

The following conclusions can be derived from the modelling analyses described above.

- Results of the 3-D numerical groundwater flow model show that groundwater levels (in the surficial silty sand and other strata) will not be affected beyond the property boundary;
- The results of the steady state groundwater model show that, post-failure of the leachate collection system, between 94% and 99% of the leachate generated at the Site will be collected in on-Site ditches, and will not leave the Site. Of the groundwater that seeps past the property boundaries, approximately 0.10% to 0.14% will be through the silty layer, while between 0.8% and 4.9% will be through the silty clay towards the glacial till/bedrock contact zone;

- The results of the hydrogeologic/contaminant transport modelling indicate essentially zero predicted impact on the silty layer at the downgradient edge of the landfill. For all parameters, the Reasonable Use Criteria for the silty layer are satisfied, noting that chloride naturally exceeds the ODWQS;
- The results of the hydrogeologic/contaminant transport modelling indicate that the contaminating lifespan of the landfill is 20 years from year 10 after filling commences (i.e. at closure of the landfill based on a 30 year planning period), which is less than the service lives of both the leachate collection system (100 years) and the GCL (greater than 1,000 years); and
- The groundwater analyses show that even if there was an early failure of the leachate collection system, then the thickness and low hydraulic conductivity of the natural silty clay deposit would provide the required off-Site groundwater protection. For this reason, as described in section 11.4, the effects of small-scale surface or subsurface displacements from local fault movement, in the very unlikely event that it occurs during the contaminating lifespan of the landfill, are inconsequential for engineering design or performance of the landfill.