Regional Municipality of Peel

Surface to Aquifer and Surface to Well Advection Time Wellhead Protection Areas in Credit Valley Watershed Caledon Village Wells 3 and 4, Inglewood Wells 1/2 and 3, Cheltenham PW1/ PW2, & Alton Wells 3 and 4.

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Report Submitted to:

Regional Municipality of Peel

AquaResource Inc.

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EXECUTIVE SUMMARY

The Clean Water Act lays out a framework that aims to identify and assess the risks to the quantity and quality of municipal drinking water sources. The Act legislates that a series of studies be undertaken and the methodologies undertaken and results of these studies will be assembled into an Assessment Report, which will form the basis of a Source Protection Plan that will outline how the municipalities in the Source Protection Region will address threats placed on the water supplies.

One of the studies legislated under the Clean Water Act by the Ontario Ministry of the Environment is the Groundwater Vulnerability Assessment. This assessment focuses on assessing the vulnerability of groundwater based water supplies to surficial sources of contamination. The Vulnerability Assessment includes the mapping and ranking of the calculated intrinsic susceptibility of the groundwater resources, and subsequently the vulnerability scoring. These outputs are then used as inputs into the Water Quality Risk Assessment.

The Groundwater Vulnerability Assessment can be undertaken using a variety of approaches including mapping of the vulnerability with the intrinsic susceptibility index method within the Time of Travel capture zones (as outlined in AquaResource, 2007) or mapping the relative vulnerability using Surface to Well Advection Time (SWAT) or Surface to Aquifer Advection Time (SAAT) methods.

The study was completed as part of the Region of Peel's Drinking Source Water Protection initiatives, and it represents a step in the continuous improvement of the hydrogeological characterization of the Region's municipal drinking water sources. The project tasks were carried in accordance with the MOE Guidance Module for Groundwater Vulnerability Analysis, Draft Module 3 (MOE, 2006). This supplementary study lays the foundation for further analysis of issues, threats and concerns to municipal drinking water supplies and the subsequent Water Quality Risk Assessment for the Peel water supply systems located in Alton, Caledon Village, Inglewood and Cheltenham. The specific systems that constituted the subject of this assessment included the wellhead protection areas (WHPA) for Alton Wells 3 and 4; Cheltenham Wells PW1/ PW2, Inglewood Wells 1, 2 and 3 and Caledon Village 3 delineated as part of the Region of Peel WHPA Study for Municipal Residential Groundwater Systems Located within Credit Valley Watershed (AquaResource Inc., 2007).

This current study examined the intrinsic vulnerability ranking and scoring of the above noted wellfields in Alton, Caledon Village, Inglewood and Cheltenham to surficial sources of contamination using two unique methodologies; (i) the Surface to Well Advection Time (SWAT) method, and (ii) the Watertable to Well Advection Time (WWAT) method. The vulnerability assessments were completed following the MOE Draft Guidance Module 3, and the vulnerability scores can be carried forward by the Region of Peel in their future Water Quality Risk Assessments. The SWAT and WWAT methodologies provided a more in depth look at the vulnerability of the municipal aquifer based on the physical nature of the groundwater flow system.

SWAT values were calculated by summing the travel time through the unsaturated zone from ground surface to the watertable (UZAT), and the saturated travel time from the watertable to the well (WWAT). Forward particle tracking in the FEFLOW model was used to determine the saturated zone travel time (WWAT), while the unsaturated zone travel times (UZAT) were calculated independently within a GIS. UZAT values were

calculated using modeled recharge rates, estimates of mobile water content and the thickness of the unsaturated zone. These two components of the travel time were combined to calculate the overall SWAT for each of the wellfields examined.

The results of the SWAT vulnerability ranking and scoring were compared to the intrinsic vulnerability assessments completed in the Peel WHPA Study (AquaResource, 2007). The SWAT analysis (and the computation of the component values) provides additional insight into the intrinsic vulnerability within a wellfield. It is understood that the ISI vulnerability method is subject to some uncertainty as it is calculated independently from the groundwater modelling, or other knowledge of the groundwater flow system. Computation of the UZAT, SAAT, WWAT, and SWAT provides insight into travel times from the ground surface to the well, and an enhanced understanding of portions of the projected capture zone that actually contribute to the well.

Of particular importance, the SWAT analysis includes a consideration of the flow system that underlies a projected capture zone and flows toward a well (ISI calculations have no such consideration). The plan-view projection of three-dimensional capture zones onto the ground surface is typically used for groundwater protection purposes. However, the vulnerability of the land surface above a capture zone is only pertinent in areas where the local flow system contributes to the underlying capture zone. Consequently, in some cases, much of the water recharged above a capture zone may be part of a local flow system that flows past a well or to other local discharge zones; this water does not contribute to the well. Such is the case in Inglewood Well 3 and Cheltenham PW1/PW2 which extract water from a deeper groundwater flow system.

In all cases, the time required for a particle to travel from the ground surface to the well is longer than for the previously mapped capture zones which ignore the time of travel through the unsaturated zone. Similarly, the time required for a particle to travel from the watertable to the well is often considerably longer than the capture zone would suggest. This occurs because the backward-tracked particles used to generate the capture zones often remain within the municipal aquifer throughout the capture zone, and may not reach the watertable.

Constructed or natural preferential pathways such as improperly abandoned boreholes or breaches in aquitards may be present within the capture zones, and these pathways may allow contaminants to move rapidly from the ground surface to the underlying aquifer. The SWAT calculations do not take these features into account, and therefore are less conservative or precautionary than reverse particle tracking to produce time of travel capture zones. WWAT calculations may also be more appropriate to account for such circumstances.

In general, the SWAT assessment has provided knowledge that is consistent with water quality observations. In comparison with the ISI values computed as part of the earlier WHPA study (AquaResource, 2007), the SWAT assessment had provided additional insight and refinement. This is largely because the SWAT assessment is more physical and takes more of the physical setting into account. The refinement is particularly important for wellfields where confining beds overlie the capture zone and limit the portion of the ground surface that actually contributes to the well / wellfield; this consideration is pertinent for the following wellfields: Alton Wells 3/ 4, Inglewood Well 3, and Cheltenham PW1/PW2.

The SWAT and SAAT methods were used to rank or categorize the vulnerability within the 25-year time of travel capture zones, and the vulnerability ranking was used to score the vulnerability within the capture zones. The SWAT analysis and the computation of the UZAT, SAAT, WWAT, and SWAT provides insight into travel times from the ground surface to the well, and an enhanced understanding of portions of the projected capture zone that actually contribute to the well.

In general, the SWAT/WWAT vulnerability ranking within the capture zones for Caledon Village Well 3, and Inglewood Wells 1/2 range from moderate to high as they are completed in unconfined to semi-confined aquifers. The SWAT/ WWAT vulnerability mapped for Caledon Village Well 4, Inglewood Well 3 and Cheltenham PW1/PW2 ranged from low to moderate as those wells are completed in confined aquifers. The SWAT/ WWAT values for Alton 3/4 were mapped as low, however these results contradict field data and as such, additional data collection is recommended to refine these results.

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1 INTRODUCTION

AquaResource Inc. (AquaResource) was retained by the Region of Peel to conduct an analysis of the Surface to Well Advection Time (SWAT) for the Region of Peel municipal wells that lie within the Credit River Watershed. These wells include Alton Wells 3/4, Caledon Village Wells 3 and 4, Inglewood Wells 1/2 and 3, and Cheltenham PW1/ PW2 (Figure 1). The Region of Peel specified that the methodologies used for this study were to be similar to those outlined in the Waterloo Hydrogeologic Inc. (WHI) 2005 report entitled "Municipal Groundwater Supply Vulnerability Pilot Study for Palgrave No. 4 and following methods outlined in MOE Groundwater Vulnerability Guidance Module 3 (MOE, 2006).

This vulnerability assessment is an extension of recently completed capture zone delineation using reverse particle tracking time of travel (TOT) method and groundwater vulnerability assessment using Intrinsic Susceptibility Index (ISI) method (AquaResource, 2007). The purpose of this additional assessment is to supplement the ISI aquifer vulnerability assessment using surface to well (SWAT) and surface to aquifer advection times (SAAT). These advection times are computed using forward particle tracking from the ground surface through the saturated and unsaturated zones to the municipal well using the groundwater modeling program FEFLOW.

1.1 Study Components and Deliverables

In accordance with the Guidance Module 3 (MOE, 2006) the key components and deliverables associated with each method of the vulnerability assessment include the following:

(i) Assess the intrinsic vulnerability within the 25-year TOT capture zones (MOE, 2006; AquaResource, 2007) utilizing the intrinsic susceptibility index (ISI) and surface to well advective time (SWAT) methods.

(ii) Intrinsic vulnerability ranking (high, medium, low) within new WHPAs (using ISI or SWAT methods); and,

(iii) Vulnerability scoring whereby a vulnerability score is assigned to each sensitivity zone (A, B, C, D) within the 25-year TOT WHPA (as per Table 4.1 of Guidance Module 3; MOE, 2006).

(iv) Discuss the uncertainties associated with the vulnerability assessment, as applicable.

1.2 Background

According to the MOE Guidance Module 3, the ISI vulnerability assessment is a minimum standard method for vulnerability assessment and was the primary method used as part of the WHPA study completed by AquaResource in 2007. Some consider the ISI method to be overly conservative as ISI calculations take into account only travel time through the unsaturated zone (to the uppermost watertable aquifer) and it does not consider the vertical travel time through the (saturated) zone to the municipal aquifer, which in many cases is overlain by lower conductivity materials (confined). Therefore, as a supplementary method, the Region requested an alternative vulnerability assessment utilizing the SAAT / SWAT approach to account for the travel time from the ground surface through the unsaturated zone to the watertable and the municipal production aquifer to the municipal well.

SAAT/SWAT calculations provide municipalities with the opportunity to apply vulnerability outputs generated based on approach that is more physically-based, linking vertical travel times to the aquifer and horizontal travel times within the aquifer. The output for the SAAT / SWAT vulnerability analysis includes maps of travel times for recharging particles of water in units of time (years), however it is recommended that the results of this analysis be viewed as a relative measure of vulnerability rather than definitive travel times for a contaminant to travel from ground surface at a point on the ground surface to a well. Thus, in addition to the deliverables noted above, the study outputs also include vulnerability ranking (high, medium, low) and vulnerability scoring (2-10) for each WHPA sensitivity zone (A, B, C, D).

1.3 Report Layout

The report includes numerous figures embedded in the text and other as report attachments at the rear of the report. For example, all histogram figures showing the advective travel time ranges are included in the text while all plan view maps are included in the ‘Figure’ portion of the report.

Regardless of the figure placement, one consecutive numbering system was applied to all figures, which corresponds to the references made in the text. The readers/users of this report are directed to both the text and the report attachments when seeking specific figure references.

2 VULNERABILITY ASSESSMENT METHODOLOGY

The current SWAT/SAAT vulnerability assessment utilized a variety of data sources including the groundwater flow model, and mapping from the Wellhead Protection Area Study (AquaResource, 2007). Specific data used in the study included WHPA capture zone/ sensitivity zone delineations and mapping, digital topographic elevation model, surficial geology mapping within each WHPA and vicinity, depth to water calculations/ mapping, recharge values, and output from the calibrated FEFLOW groundwater model. The MOE's terminology, supporting diagrams and tables, as per the Guidance Module 3, were also utilized to better depict study methodology.

2.1 WHPA TOT Delineations vs SWAT/SAAT TOT Assessment

The WHPA study outputs that are relevant to the current assessment included the 'time-of-travel' (TOT) capture zone delineations (100 m, 2-year, 5-year, and 25-year) and the corresponding WHPA sensitivity zone mapping (A, B, C, D). The MOE Guidance Module 3 specifies that the vulnerability assessment be undertaken within the 25-year time of travel (TOT) capture zone, and subsequently, the vulnerability scoring must be undertaken within each of the WHPA sensitivity zones (A, B, C and D).

The WHPA capture zone delineation methods are discussed in Section 4 and Appendix 2 of the MOE's Guidance Module 3 (2006) and the approaches employed in the WHPA study for Peel municipal wells located within the Credit River watershed are discussed in Sections 2.1, 2.2 and 3.5 of the WHPA Study report by AquaResource (2007). The outputs of the reverse particle tracking carried as part of the WHPA Study reflect the upward projection of the 'time-of-travel' results onto a plan view. As the time of travel delineations do not account for full vertical flow through the subsurface, they are considered to be very conservative. At the same time, this conservatism compensates for potential direct preferential pathways such as improperly abandoned boreholes that can rapidly transmit contaminants from surficial or subsurface sources to underlying aquifers. This conservative capture zone delineation is the MOE recommended WHPA delineation method.

Relative ISI vulnerability assessment and vulnerability scoring utilizing the ISI rating and WHPA sensitivity zones were presented in Sections 2.4 and 3.6 of the WHPA study by AquaResource (2007). The ISI method does not provide the estimates of groundwater travel time; it provides means of assessing intrinsic vulnerability based on the geologic characteristics of material overlying the aquifer of interest. The ISI method is considered by the Ontario Ministry of the Environment (MOE) as the minimum standard for vulnerability assessment.

While the SWAT/SAAT methods, as discussed in Sections 1.2 and 2.2 of this report, attempt to account for the actual travel times from the surface to the well screen/ aquifer and thus are less conservative, they are used to estimate the relative vulnerability (High, Medium, Low) similar to the ISI method, however the SWAT/ SAAT methods are based on the actual calculated travel time using forward particle tracking. The SWAT/ SAAT methods are discussed in detail in Section 2.2.

2.2 Vulnerability Assessment: SWAT/SAAT Method

The SWAT/SAAT zones were calculated and mapped according to the methodologies outlined in the MOE Assessment Report: Draft Guidance Module 3 (MOE, 2006). The

SWAT/ SAAT methodology incorporates the travel time through both the saturated and unsaturated zones, and therefore is considered to be a less conservative and more physically-based estimate of vulnerability.

Calculating the SWAT is completed as the sum of two components; the watertable to well advection time (WWAT), and the unsaturated zone advection time (UZAT; Figures 2 and 3). These two components represent travel through the saturated and unsaturated zones respectively. The total time required for a fictitious particle of water to travel from the ground surface to the well is the sum of the unsaturated travel time (which is assumed to be vertical travel only), and the saturated travel time components. The saturated travel pathway will include both vertical and horizontal flow components, and is typically determined through forward particle tracking from the watertable to a municipal well.

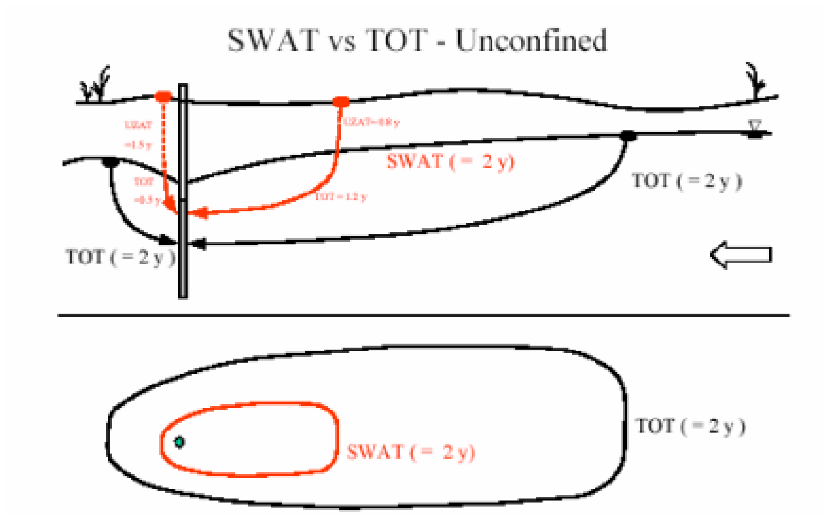

Figure 2: Comparison of SWAT and Time of Travel Delineations for Unconfined Aquifers

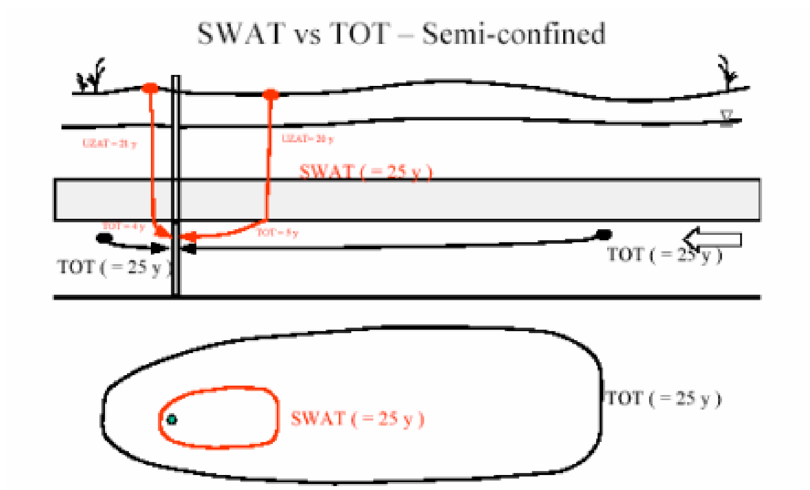

Figure 3: Comparison of SWAT and Time of Travel Delineations for Confined Aquifers

The SAAT calculation differs from the SWAT calculation in that it accounts for travel time from the ground surface to the top of the municipal aquifer rather than ground surface to the municipal well. The SAAT calculation includes the unsaturated travel time and the portion of the travel time within the saturated zone that is required to reach the municipal aquifer. In cases where there is no distinct aquitard unit between the municipal aquifer and the ground surface, the SAAT is equal to the UZAT. In cases where a distinct aquitard unit overlies the municipal aquifer, the SAAT includes the UZAT plus the time required for advective migration through the aquitard (to the top of the aquifer) within the saturated zone.

The information utilized for the SWAT/SWAT methods included digital topographic elevation model (depicted on Figure 2 of the WHPA report; AquaResource, 2007), surficial geology mapping within each WHPA and vicinity (Figure 6, and Figures 9-12 of the 2007 WHPA Report), depth to watertable mapping (see Figures 4 to 8 of this report) and recharge values (Figure 13 of the WHPA Report (AquaResource, 2007)).

2.2.1 Watertable to Well Advection Time - Saturated Zone Travel Time

The software program FEFLOW was used to conduct the forward particle tracking for the WWAT assessment. Particles were released on the watertable surface (as delineated with the calibrated groundwater flow model; see Figures 4 to 8) at a 50 m grid spacing within the delineated 25-year capture zones for Alton 3/4, Caledon Village Wells 3 and 4, Inglewood Wells 1/2 and 3, and Cheltenham PW1/PW2 (AquaResource, 2007). To be conservative and allow for differences between the forward and reverse particle tracking, particles were also released within a 250 m buffer zone around the delineated 25-year capture zones (see Figures 9 to 12 for plan view of particle release distribution). The time of travel SWAT and WWAT polygons (0-5 year, 5 to 25-year and >25 year) were then delineated from the resultant particle distribution and ranked accordingly (high, medium and low). These polygons were overlaid with the WHPA time of travel capture zones and a vulnerability score was assigned for use in subsequent Water Quality Risk Assessments.

This approach assumes that all particles that would reach the well within a reasonable time limit originate within the 25-year capture zone (i.e., the sum of the WWAT and UZAT would be much greater than 25 years); this approach is also consistent with the methodologies outlined in the MOE Guidance Document (MOE, 2006). The particles were tracked forward in time until they reached a boundary condition in the model such as a river, stream, or the municipal pumping well.

Not all particles released at the watertable within the 25-year capture zone reach the well; some discharge to surface water features (Figure 4 to 8) within and outside the capture zone. This observation reinforces the conceptual understanding that the capture zone is a plan view projection of the zone that contributes water to a well and, particularly in multi-aquifer systems, shallow aquifer systems can be independent of flow within deeper municipal aquifers. Those particles that did not reach a municipal well were removed from the WWAT and SWAT analysis. The release point for particles that reached a municipal well was noted, along with the travel times to reach the well. This information was subsequently transferred to the project GIS with data corresponding to the easting and northing of the release point and the time estimated for the particle to travel from the watertable to the municipal aquifer or the well. This information was used to calculate the saturated portion of the SAAT and the WWAT. For unconfined aquifer systems, the top of the municipal aquifer is considered to be the watertable and therefore the surface to aquifer time is coincident with the unsaturated zone travel time (see Section 2.1.2 below).

2.2.2 Surface to Watertable Advection Time- Unsaturated Zone Travel Time

As outlined in the MOE Guidance Module 3 (MOE, 2006) the unsaturated zone advection time (UZAT) is a vertical travel time through the unsaturated zone. It is proportional to the thickness of the unsaturated zone, the degree of saturation, and the estimated rate of groundwater recharge. As per the MOE, it is applied where the depth to watertable is greater than 3 m for both unconfined and confined aquifers.

The project GIS was used to calculate the depth to watertable (Figures 4 to 8) component of the UZAT equation and the final UZAT value. The depth to watertable was first calculated by subtracting the ground surface digital elevation model from the watertable elevation calculated using the calibrated groundwater model. Recharge estimates applied in the FEFLOW model were also exported from the model into the GIS for analysis (Figure 13 in the WHPA Report; AquaResource, 2007). The time for a particle to travel through the unsaturated zone from the ground surface to the watertable was calculated using the following equation:

$$\mathrm{UZAT} = \frac{d_{wt} \cdot \theta_m}{q_s}$$

Where d_{wt} is the depth to the watertable, Θ_m is the mobile moisture content (where lithology is determined from surficial mapping and the groundwater model layers), and the q_s is the recharge rate applied in the calibrated groundwater model.

The mobile moisture content for unsaturated overburden (as per the surficial geology maps and hydrostratigraphy within each WHPA; AquaResource, 2007) were assigned values in accordance with Appendix 3f.1 of the Groundwater Vulnerability Guidance Module (MOE, 2006): 10% for sands (material with a $K > 10^{-5}$ m/s), 25% for loam (material with a 10^{-7} m/s $> K > 10^{-5}$ m/s), and 40% for clay ($K < 10^{-7}$ m/s). Using this methodology, the unsaturated travel time in an area of outwash sand and gravel unit with a vadose zone thickness of 15 m would be approximately 4.5 years.

The concept of unsaturated zone advective travel time is only applicable within recharge area portions of capture zone and the UZAT values would be of most interest when the watertable is relatively deep. In discharge zones, the unsaturated travel time is zero. The unsaturated zone advection time was then added to the watertable to well advection time to establish the SWAT estimates surrounding the Region of Peel municipal wells (i.e., UZAT + WWAT = SWAT).

As per the MOE's Guidance Module 3 (Appendix 3g), in some cases the UZAT calculations could be refined or eliminated in consideration of local hydro(geological) conditions and uncertainties, and local land uses and potential threats; and where soil fractures/disturbances in the upper portion may provide short-circuit of contaminants through the zone.

In general, when the UZAT portion is included in the SWAT analysis, the calculated travel times are increased, and the size of the SWAT zones are decreased. It is reasonable to include the UZAT times in the SWAT analysis when considering certain contaminants such as road salt or agricultural fertilizers. In other circumstances, such as contaminant spills, the time of travel may be much less than that predicted by the methods outlined in the MOE Guidance Module 3. It is important to recognize the uncertainty associated with the parameters used in the calculations of the various methodologies (SWAT, SAAT, UZAT, etc), and in some instances, it may be pertinent to disregard the UZAT calculations in the SWAT analysis, and for this reason, the results of the WWAT analysis have also been included.

2.3 Relative Vulnerability Assessment and Scoring: SWAT Method

Appendix 4 of the MOE's Guidance Module 3 deals with Intrinsic Vulnerability Mapping and Scoring applicable to all vulnerability assessment methods and all 'highly vulnerable areas' defined by the MOE, including the WHPAs (Appendix 4d). In this Appendix, the Guidance outlines how the results of the vulnerability assessments (ISI or SWAT) can be used to complete the vulnerability scoring as it is the vulnerability score that is carried forward into the risk assessment portions of the Source Protection Assessment Report.

The primary MOE reference that relates to relative vulnerability rating and scoring is Table 4.1 in Appendix 4 (or Table 1 of the MOE Guideline Module 3). In general, the scoring process includes the following steps:

- i categorizing the relative vulnerability of the aquifer as high (0<H<5 years), medium (5 years<M<25 years), or Low (L>25 years);
- ii overlying/intersecting the WHPAs sensitivity zones A, B, C, D with the vulnerability rating/ categorization (high, medium, low); and
- iii assigning the intrinsic vulnerability score between 2 (low vulnerability) and 10 (high vulnerability).

In accordance with the MOE's Guidance Module 3, Table 4.1, the vulnerability scoring applied to the SWAT and WWAT zones delineated in this study is outlined in Table 1.

Table 1: SWAT and WWAT Vulnerability Scoring

<table>
<tr><th rowspan="2">WHPA TOT Zones</th><th colspan="3">Intrinsic Vulnerability Scoring (IVS): SWAT/ WWAT</th><th colspan="3">Comments</th></tr>
<tr><th>High IVS (0-5yr)</th><th>Medium IVS (5-25yr)</th><th>Low IVS (>25yr)</th><th>Pathogen</th><th>DNAPLs</th><th>Zone Designation</th></tr>
<tr><td rowspan="2">Zone A (100 m radius)</td><td>10</td><td>10</td><td>10</td><td rowspan="2">10</td><td rowspan="2">10</td><td rowspan="2">Pathogen security/prohibition zone</td></tr>
<tr><td colspan="3">High scoring irrespective of SWAT/WWAT score</td></tr>
<tr><td rowspan="2">Zone B (0-2 yrs)</td><td>10</td><td>8</td><td>6</td><td rowspan="2">6-10 (IVS=10 in 100m zone)</td><td rowspan="2">10</td><td rowspan="2">Pathogen management zone: all contaminants but DNAPLs</td></tr>
<tr><td colspan="3">Scoring applies to all contaminants but DNAPLs</td></tr>
<tr><td rowspan="2">Zone C (2-5 yrs)</td><td>8</td><td>6</td><td>2</td><td rowspan="2">0</td><td rowspan="2">10</td><td rowspan="2">DNAPL contaminant protection zone</td></tr>
<tr><td colspan="3">Scoring applies to all contaminants but Pathogens & DNAPLs</td></tr>
<tr><td rowspan="2">Zone D (5-25 yr)</td><td>8</td><td>6</td><td>2</td><td rowspan="2">0</td><td rowspan="2">2-8</td><td rowspan="2">Secondary Protection Zone</td></tr>
<tr><td colspan="3">Scoring applies to all contaminants but Pathogens</td></tr>
</table>

2.4 Uncertainty Assessment

As outlined in the Groundwater Vulnerability Guidance Module (MOE, 2006), an uncertainty rating of either 'high' or 'low' must be assigned to each wellhead protection sensitivity area (or subsection of a polygon) within each municipal capture zone. The uncertainty rating applied should consider the uncertainty associated with quantity and quality of data used to assess the vulnerability, with delineating the time-of-travel capture zones, and with determining the relative vulnerability rating (high, medium, low) using ISI or SWAT methods. If a high relative uncertainty rating is applied to a polygon for either assessment (time-of-travel delineation or vulnerability rating), the uncertainty rating for that polygon is defined as 'high' (MOE, 2006). Only if the uncertainty ratings associated with both the time-of-travel and the vulnerability rating were determined to be low would the resultant uncertainty score be defined as 'low'.

2.4.1.1 Uncertainty Associated with Time of Travel Delineations

Uncertainty in the delineation of the capture zones, SWAT or WWAT travel times was minimized through the simulation of multiple sensitivity scenarios. In general, the sensitivity scenarios for WHPA delineation produced similarly shaped capture zones, resulting in a relatively low uncertainty for the capture zone delineation. The uncertainty in SWAT or WWAT travel times was also addressed through multiple model sensitivity runs.

2.4.1.2 Uncertainty Associated with Vulnerability Rating

There are several levels of uncertainty associated with determining the vulnerability rating (high, medium, low) that vary depending on the method used (ISI or SWAT). One of the main uncertainties associated with the vulnerability rating common to both methods is the quality and quantity of data available to interpret the geologic and numerical model layers. Sparse water well data or poor quality well data can lead to uncertainties in the thicknesses of aquifers and aquitards, which in turn increase the uncertainty associated with the ISI based vulnerability calculations or the SWAT/ WWAT travel times.

There are several uncertainties associated with the input parameters used to calculate the SWAT and WWAT travel times and categorize the vulnerability (e.g. high, medium or low). Calculating the UZAT times requires estimates of mobile moisture content within the unsaturated zone, recharge values, and depth to watertable, and there are uncertainties associated with each of these parameters. The depth to watertable used was based on the watertable elevation from the calibrated groundwater model, and represents the average annual condition. However, the depth to watertable will vary seasonally as precipitation (and recharge) rise and fall. The recharge estimate used in the UZAT calculation also represents average annual recharge, and also does not take seasonal variations in recharge into account. In addition, the mobile moisture content is assumed to be constant throughout the unsaturated zone, and constant throughout the year, however the mobile moisture content in the unsaturated zone fluctuates on an event or seasonal basis. Given these assumptions, the unsaturated travel time values are generalized and may overestimate the actual travel times from ground surface to the watertable.

The hydraulic conductivities applied in the groundwater model also have a similar degree of uncertainty. Decreasing the hydraulic conductivity in the municipal supply aquifer simulated in the model from $2x10^{-5}$ m/s to $1x10^{-5}$ m/s would equate to increases in the SWAT travel times from 3 years to 6 years, or 15 years to 30 years. This minor adjustment to the hydraulic conductivity would in turn lead to a shift in the SWAT vulnerability rating from high to medium, or medium to low.

3 RESULTS

3.1 Alton Wells 3/ 4 and Caledon Village Well 4

This section describes the results of the SWAT/ SAAT vulnerability assessment for Alton 3/4, Caledon Village 4, Caledon Village 3, Inglewood 1/2 and 3, and Cheltenham PW1/PW2. Maps, figures and tables depicting information utilized in this assessment were presented in the WHPA report by AquaResource Inc. (2007) and are referenced accordingly in this report.

3.1.1 Hydrostratigraphy

Hydrostratigraphy in the Alton area is highly variable with both overburden (sand and gravel) and bedrock (Amabel Formation) aquifers present in the area (Figure 9 and Appendix A; AquaResource, 2007). Thick unconfined sand and gravel aquifers associated with the Orangeville Moraine dominate the topography west of Alton. Within the Village, overburden thins or pinches out completely and bedrock outcrops at ground surface along the banks of Shaw's Creek in some areas. Alton Wells 3/4 are screened approximately 20 m below the surface in an unconfined overburden, sand and gravel aquifer.

The bedrock valley that loosely underlies the modern day Credit River also hosts overburden aquifers, including the municipal aquifer intersected by Caledon Village Well 4. The buried bedrock valley aquifers in this area are semi-confined to unconfined as the regional confining layer (Port Stanley Till Plain) was eroded by a meltwater channel associated with the Credit River. There is a thin fine-grained organic deposit lying at surface in the vicinity of Caledon Village Well 4, and is associated with the 'Credit River at the Alton, Provincially Significant Wetland' (AquaResource, 2007). The municipal well extends over 70 m below the ground surface and intersects a deep sand and gravel overburden aquifer.

3.1.2 Groundwater Flow System

Groundwater flow in the Alton area extends from the Orangeville Moraine in the west towards the Credit River in the east (Figure 18 of AquaResource, 2007). The relatively coarse-grained nature of the overburden and highly transmissive nature of the bedrock formation results in considerable groundwater flow through the area, of which only a portion is captured by the Alton 3/4 wells. The high transmissivity and relatively low wellfield pumping rate result in a narrow capture zone for the Alton 3/4 wellfield (Figure 27; AquaResource, 2007).

Groundwater flow occurs through the unconsolidated overburden deposits as well as the underlying Amabel Formation bedrock. The Alton wells are located within a natural, regional discharge zone associated with the Credit River and the nearby buried bedrock valley; the model simulates the wells to capture water from the shallow overburden deposits west of the wells (Orangeville Moraine). A significant component of the water being captured by the wells is from a distant recharge area; water recharges on the Orangeville Moraine west of Alton and travels along regional flow paths, primarily through the upper unconfined aquifer, before reaching the well or discharging to the Credit River or nearby wetlands. Figures 13a and 13b illustrate forward particle tracks which are captured by Alton Wells 3 / 4 and those that flow past the wells, respectively. For visualization purposes, the particle tracks are projected along a cross-section that extends down the centre of the 25-year time of travel capture zone for Alton 3/4. In general, particles released at the watertable and tracked forward in time, travel along the unconfined overburden system for large distances (6 km) before discharging at or near the municipal wells.

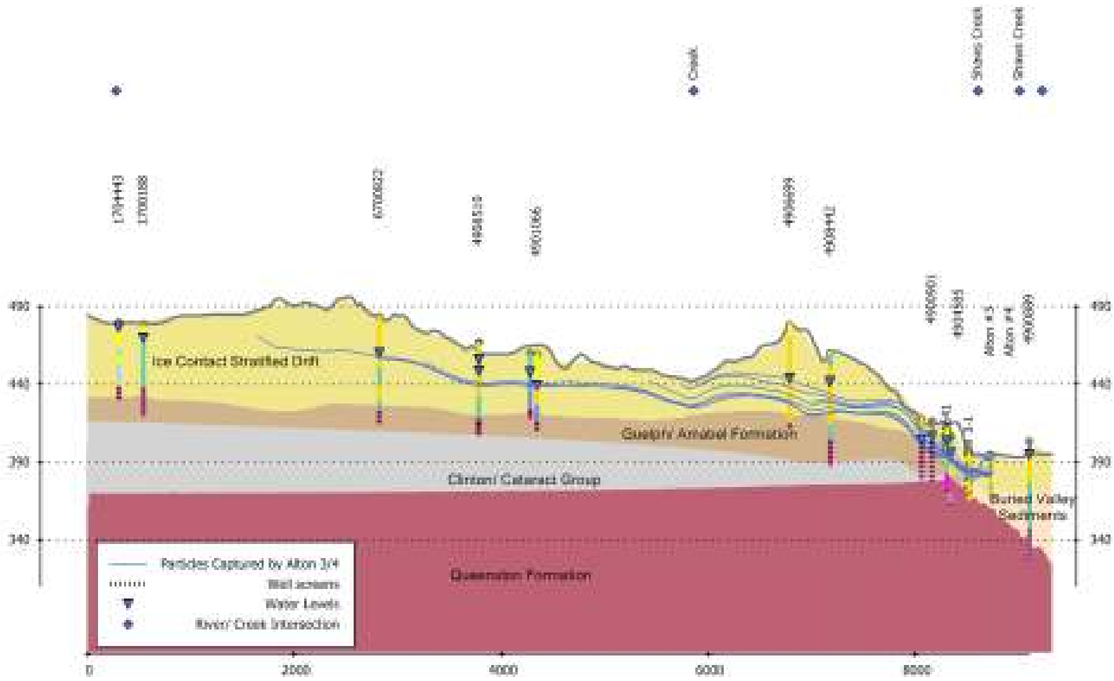

Figure 13a: Flow Paths Traveling To Alton Wells 3/4

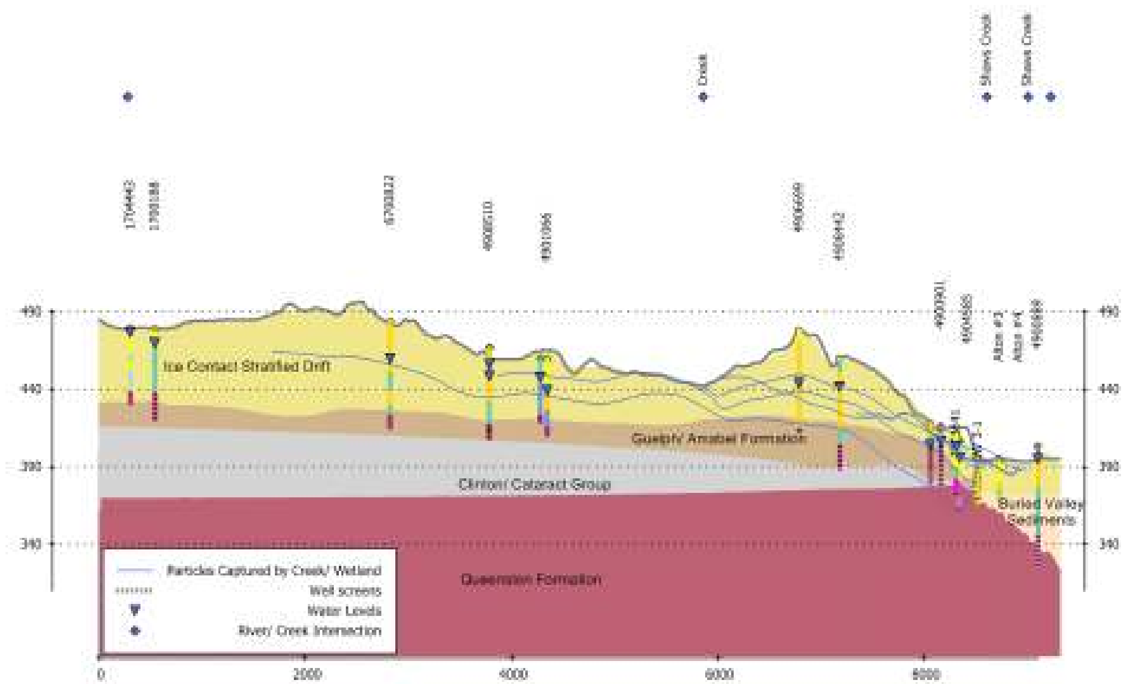

Figure 13b: Flow Paths Traveling Past Alton Wells 3/4

These figures illustrate that flow originating within similar areas are captured or flow past the municipal wells. This is further evidence that the municipal well is capturing a relatively small portion of the water flowing through this area. A more detailed discussion of the Alton Wells 3/4 capture zone is contained within the Region of Peel WHPA Study Report (AquaResource, 2007).

3.1.3 SAAT/UZAT

In the area surrounding Alton Wells 3/4, the municipal supply well is largely unconfined and therefore, the top of the municipal aquifer was considered to be the watertable position. As a result, the SAAT within the 25-year capture zone of Alton Wells 3/4 was interpreted to be coincident with the UZAT. The UZAT times range from a high of approximately 20 years (located southwest of the wellfield where unsaturated sand and gravel deposits predominate) to a low of 0 yrs for those points located within discharge zones. Figure 14 is a histogram illustrating the UZAT times for the particles released in the Alton 3/4 wellfield area. Overall, the unsaturated travel time was found to be between 2 and 15 years, with the majority of particles reaching the watertable in the range of 5 to 10 years. In the immediate vicinity of the wellfield, the travel time through the unsaturated zone was calculated to be less than 1 year.

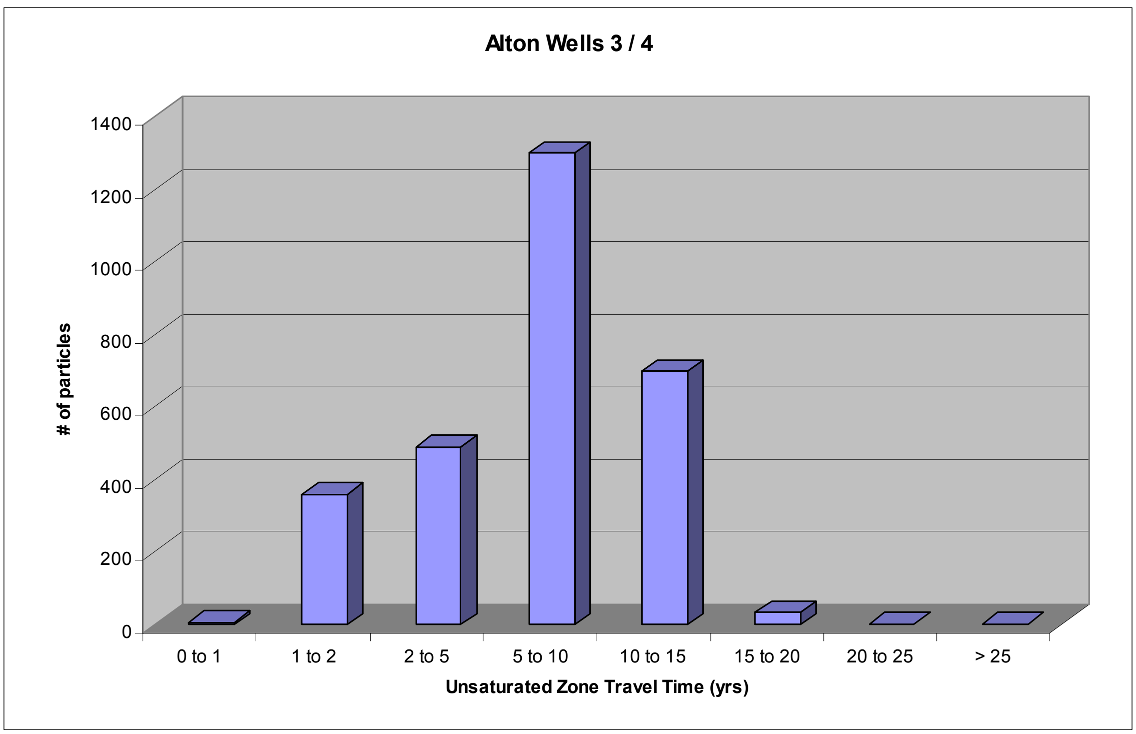

Figure 14: Histogram of the Unsaturated Zone Advection Time for Alton Wells 3/ 4.

Similarly, UZAT values within the Caledon Village Well 4 capture zone range from 0 to greater than 20 years (see Figure 15). As in the Alton 3/4 wellfield area, the majority of the Caledon Village Well 4 area was calculated to have an unsaturated advective travel time of 5 to 10 years. As the hydrogeologic setting surrounding Caledon Village well 4 is more heterogeneous than in Alton 3/4, there is a much wider distribution within the UZAT histogram. The longest unsaturated zone travel times were estimated to be 500 m to 1 km northeast of Caledon Village Well 4, where an aquitard is mapped at ground surface (See Figure 16). The majority of the area immediately adjacent to the well and northeast of Willoughby Road has a high watertable with a relatively thin unsaturated zone, resulting in UZAT values of less than 1 year to 2 years.

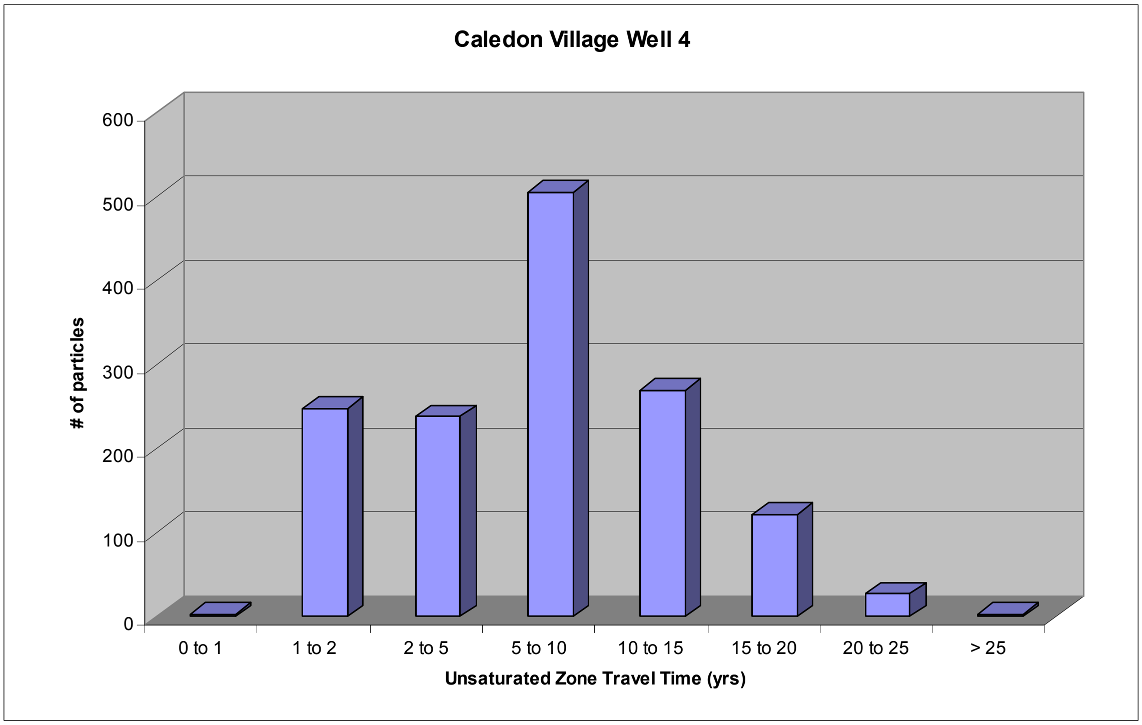

Figure 15: Histogram of Unsaturated Zone Advection Time for Caledon Village Well 4

Figure 16 is the first of several maps that illustrate the results of the forward particle tracking undertaken to produce the SWAT and WWAT zones. The colour ramp illustrated on Figure 16 and the subsequent figures is a standard colour ramp selected for its ability to clearly illustrate the differences between the advective time categories. The red/ orange colours on the map should not be viewed as indicating areas that have a contrast in water quality, or areas that require an elevated level of protection or caution. The colour ramp was chosen to provide contrast and to ease the interpretation of the advective times on the respective maps.

Figure 16 illustrates the unsaturated zone travel times within the 25-year capture zone for the Alton Wells 3/4 and Caledon Village Well 4. The red shaded dots have an unsaturated travel time of less than 2 years, orange dots have UZAT values between 2 and 5 years, and the yellow dots represent travel times of 5 to 10-years. As Figures 14 and 15 above noted, and Figure 16 spatially illustrates, the majority of the unsaturated times are less than 10 years, and less than 2 years in the area surrounding the wellfield. The relatively low attenuation within the unsaturated zone around the well is expected at this location due to the close proximity to Shaws Creek, the Credit River and the wetland complex located north of the wells. As a portion of the wellfield (near the well) is considered to be unconfined, the UZAT times were conservatively considered to be representative of SAAT times.

There are areas within the UZAT map area where the particles are absent from the analysis, and gaps exist within the UZAT map. These are areas that coincide with ponds, wetlands or similar surface water features that are simulated in the groundwater model as discharge features. Locations simulated as discharge features generally have a watertable predicted by the groundwater flow model to lie at ground surface, and therefore an unsaturated zone travel time equal to zero. Figure 16 illustrates the location of the surface water (wetland, river, creek) boundary conditions applied in the model.

3.1.4 WWAT

The distribution of watertable to well advection time (WWAT) values for Alton 3/4 and Caledon Village 4 WHPA (and the 250 m buffer) are illustrated on histograms in Figures 17, and 18. These histograms show that the travel times from the watertable to the municipal wells ranged from 1 year to over 50 years, with the majority of travel times being over 20 years.

3.1.4.1 Alton Wells 3/4

For the majority of the Alton 3/4 capture zone, the forward particle tracking from watertable to the well (WWAT) is longer than the 25-year WHPA TOTs projected to surface based on reverse particle tracking from well screen to top of aquifer; the difference between the two estimates suggests that the travel time from the watertable to the municipal aquifer is greater than 15 years. Figure 19 illustrates the spatial distribution of particles released on the watertable that reach the municipal well. In the Alton area, there are very few particles released within the 25-year time of travel capture zone that reach the municipal well; before reaching the well, some particles discharge to local surface water features, or travel in deeper aquifer systems towards the Credit River and the buried bedrock valley. Particles that did not reach the municipal well were not included on Figure 19 and were not part of the WWAT or SWAT analysis.

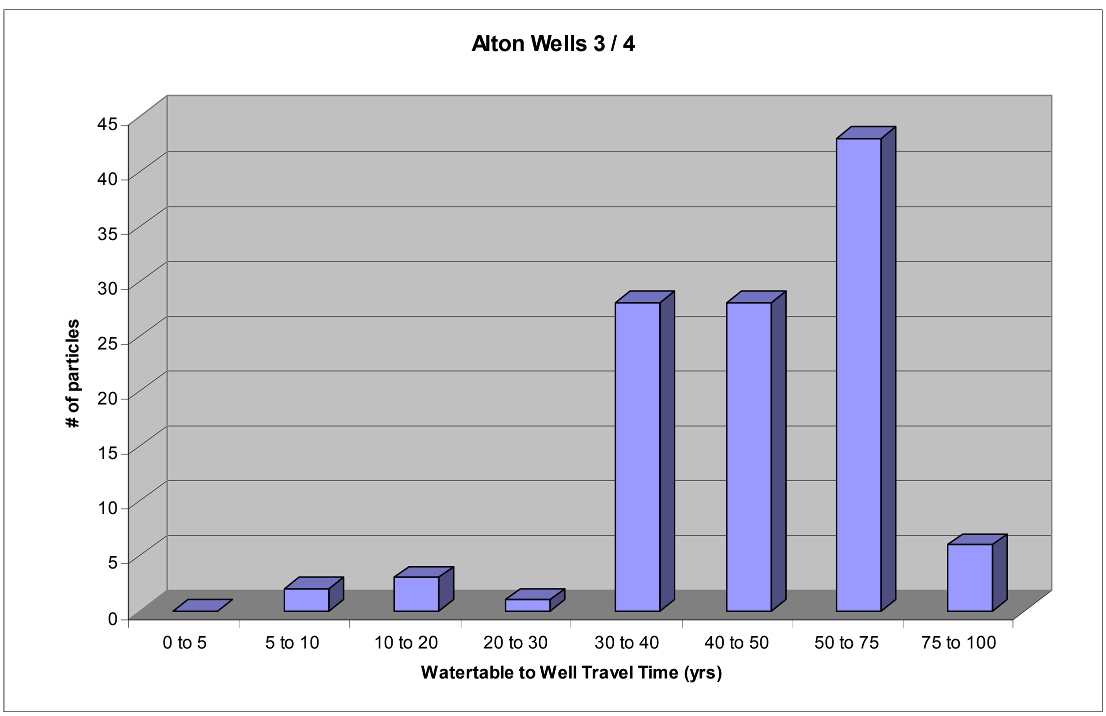

Figure 17: Histogram of Watertable to Well Advection Travel Time for Alton Wells 3/ 4.

Particles released on the watertable in the Alton 3/4 capture zone that reached the municipal well have fairly long WWAT travel times. This is because the model is predicting a large portion of the water captured by the Alton 3/4 wells is coming from a more regional groundwater system that originates on the Orangeville Moraine west of the wells. The sand and gravel moraine is characterized as a regional recharge area that supplies water to the deep aquifers (Figures 13 a,b).

As noted on Figure 19, there are few particles simulated by the model to reach the municipal well; for this reason, the relative vulnerability rating determined using the WWATs are not recommended as suitable to carry forward into the Water Quantity Risk Assessment.

3.1.4.2 Caledon Village Well 4

Figure 18 presents the histogram of watertable to well travel times for Caledon Village Well 4. As this histogram illustrates, the WWATs within the capture zone vary from 1 year to more than 100 years, with the most frequent travel time of 30 to 40 years.

As observed in Alton, the increased WWAT for Caledon Village 4 reflects the additional time required for a particle of water to flow from the watertable to the underlying capture zone, particularly where the municipal aquifer is overlain by an aquitard of significant thickness. The WWAT timing near the capture zone (500 m radius) varies from 2 years to 30 years, reflecting the hydraulic influence of the surficial aquitard in that area.

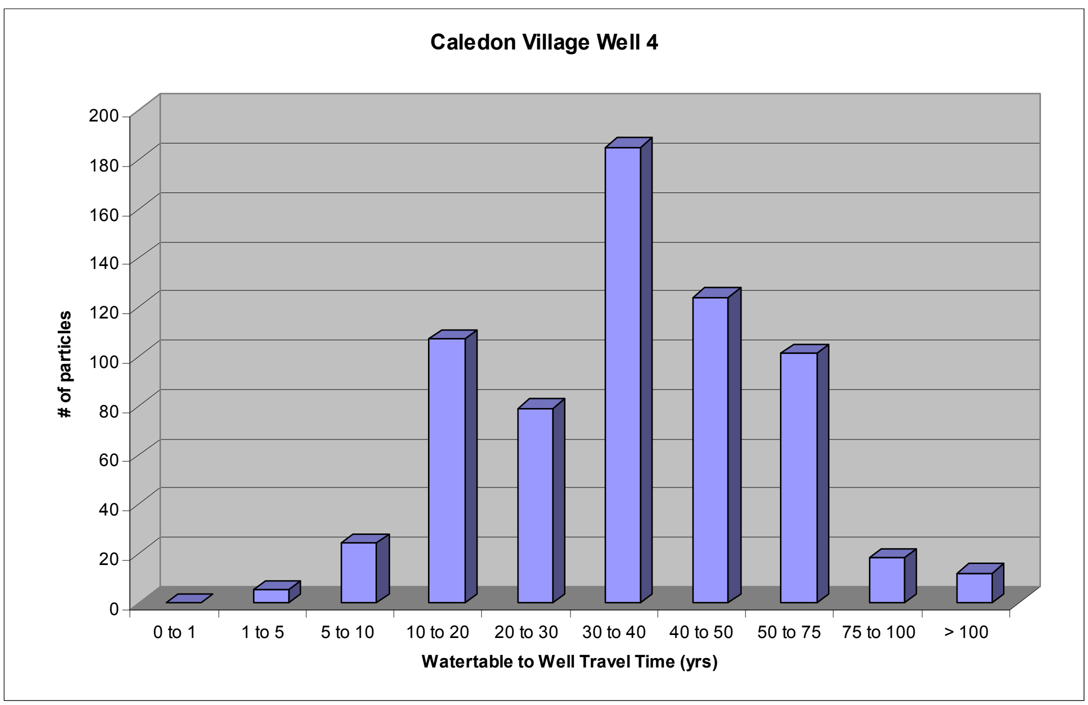

Figure 18: Watertable to Well Advection Travel Time for Caledon Village Well 4.

Figure 19 illustrates the WWAT times for particles that extend from the watertable to the municipal well. The WWAT times that vary from 5 to 25-years extend in the same direction as the 25-year capture zone, however the area containing the 5 to 25 year particles is considerably smaller than the 25-year capture zone. As noted above, the time of travel capture zones represent the backward tracking of particles from the municipal well for 25 years. In the case of Caledon Village, the backward tracking particles travel primarily horizontally through the municipal aquifer, and the capture zone represents the vertical projection of these particle pathways to the ground surface. The

WWAT particle times, in contrast, represents the pathways particles take to travel from the watertable vertically through underlying saturated aquitard(s), and then horizontally to the municipal aquifer. The additional travel time required to travel vertically through the aquitards overlying the municipal aquifer lead to smaller WWAT times than the time of travel capture zones.

3.1.5 Intrinsic Vulnerability Scoring- WWAT- Alton and Caledon Village 4

Figure 20 illustrates the intrinsic vulnerability rating (High, Moderate, Low) mapping based on the watertable to well advection times for Alton Wells 3/4 and Caledon Village Well 4. The majority of the 25-year WHPA TOT for Alton 3/4 is mapped as low, as the WWAT travel times are predominately greater than 25 years. There were no particles that traveled from the watertable to the well in less than five years and as such, there are no areas ranked with a high WWAT vulnerability. The WWAT vulnerability rating in Caledon Village well 4 is predominately medium to low, with a small area mapped as being highly vulnerable near the municipal well (Figure 20). In summary, the vulnerability ranking is predominately low using the WWAT method, which is in contrast to the predominately high and medium vulnerability mapped using the ISI-based method.

Figures 21 to 23 illustrate the WWAT vulnerability scores within those zones. The scoring was conducted for three distinct classes of contaminants: General contaminants, Pathogens, and DNAPLs as per Table 4.1 in MOE's Guideline, and outlined in Table 1 of this report.

3.1.6 SWAT

The surface to well advection time for particles released within the 25-year WHPA capture zone were computed as the summation of the unsaturated zone and the saturated zone travel times (UZAT + WWAT). For locations where the capture zone is located at a significant depth beneath the watertable and/or ground surface, the SWAT can be considerably higher than the capture zone travel time. As a result, the SWAT provides insight into the intrinsic vulnerability of the municipal well. For example, areas with a SWAT value higher than 25 years are afforded additional protection by the sediments overlying the municipal aquifer.

3.1.6.1 Alton Wells 3/4

As is shown in Figure 24, the majority of the particles that travel from surface to the municipal well within the 25-year capture zone have demonstrated travel times of 50 to 75 years.

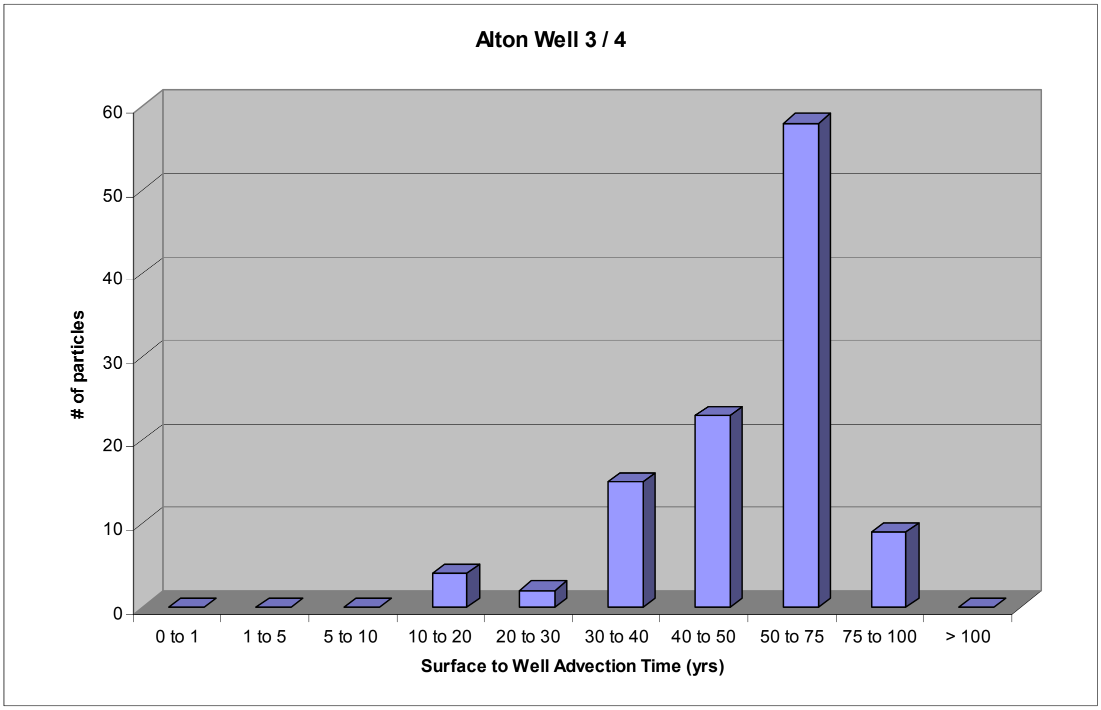

Figure 24: Histogram of the Surface to Well Advection Travel Time for Alton Wells 3/4

Within the Alton capture zone, there are only a few locations where the SWAT timing is less than the 25 year threshold. This observation reflects WWAT observations presented above.

A SWAT value greater than 25 years is inconsistent with the predicted ISI vulnerability assessment (AquaResource, 2007 – Section 3.6.1.1), which found the area to be dominated by high to medium vulnerability based on the coarse-grained materials in the area. However it must be noted that the ISI vulnerability analysis did not consider the travel time through the unsaturated groundwater flow system or vertically through the aquifers. In some cases the travel time is relatively short, and in other cases, such as the Orangeville Moraine to the west, the travel times are much longer.

SWAT travel times greater than 25 years but less than 50 years are consistent with local chemistry observations, as discussed in AquaResource (2007a). Results of water quality testing on the early warning wells (AMEC, 2004) and the municipal well (Beatty, 2005) show that sodium, chloride, and at times nitrate occur at elevated concentrations in this area, and the concentrations of sodium and chloride have been rising over the last 30 years. The source of these contaminants was interpreted to be surficial land use activities near the wellfield, which may include road salting practices, septic systems, and fertilizer application (AMEC, 2004; Beatty, 2005). Tritium isotopic dating conducted by Stantec (2002) also supports the vulnerability mapping, as the water in the Alton 3/4 municipal well was estimated to be less than 50 years old. The SWAT analysis indicated that the water being captured by Alton Wells 3/4 consists of local recharge and a degree of more regional recharge from the Orangeville Moraine, as such it is expected that the chemistry observed at the well is a mixture of local and regional recharge contributions. From Figure 26, the area of most significant local contribution is shown to be the western portion of Alton, north of Shaw's Creek.

Figure 26 presents a map of the SWAT particle travel times, and the associated vulnerability rating for Alton Wells 3/4. The SWAT travel times are comparable to the WWAT times within this area; there were no particles that traveled from the surface to the well in less than 5 years (Figure 26), and therefore there are no areas of the 25-year TOT capture zone categorized as having a high vulnerability (0-5 year SWAT). There are a few particles that reach the well with a SWAT between 5 years and 25 years and as such, there are a few isolated areas ranked with a moderate vulnerability.

Note that because of the hydraulic setting in Alton whereby the particles released at watertable travel from the Orangeville Moraine along regional groundwater flow paths towards the well, not many of the particles released at surface within the capture zone were captured by the well. Many particles flow in the direction of topographic lows and water bodies (Figure 10) and are stopped at surface water features. The pumping rate used to delineate the capture zones (using backward tracking particles) is relatively modest when compared to the transmissivity of the municipal well, and this contrast helps explain the long and thin nature of the Alton Well 3/4 capture zone. As there were a limited number of particles that reached the Alton 3/4 wells in the SWAT/ WWAT assessment, it is recommended that the vulnerability ranking and scoring results (Figure 20 to 23) not be carried forward to the Water Quality Risk Assessment. Additional characterization is recommended in this area west of Alton to refine the conceptual and numerical models and more accurate rank the vulnerability in this area.

Uncertainties associated with the Alton 3/4 capture zone, and the resulting forward particle tracking results (including the resultant SWAT/ WWAT vulnerability ranking) are noted below in Section 3.5.

3.1.6.2 Caledon Village Well 4

Figure 25 presents the histogram of SWAT particles released within the 25-year capture zone of Caledon Well 4. A portion of the SWAT particles had a travel time of less than 25 years, the majority of the particles had SWAT values in the range of 50 to 75 years.

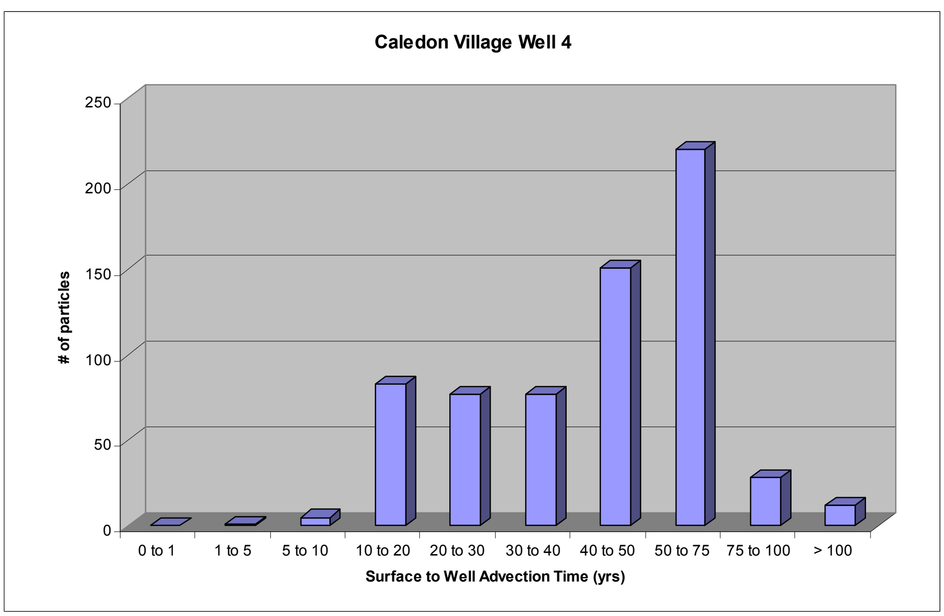

Figure 25: Histogram of the Surface to Well Advection Travel Time for Caledon Village Well 4.

The SWAT assessment for Caledon Village Well 4 is consistent with available chemistry data. Review of available water quality sampling shows that water quality in Caledon Village Well 4 and the nearby Early Warning Wells is generally good. Chloride, nitrate and sodium levels recorded in the well are generally low (AMEC, 2004; Beatty, 2005). Results of tritium isotopic dating (Stantec, 2002) estimate the age of water in Caledon Village Well 4 is older than 40 years, which is consistent with the SWAT histogram (Figure 25).

3.1.7 Intrinsic Vulnerability Scoring- SWAT- Alton and Caledon Village 4

Figures 26 and 27 illustrate the SWAT times and the resultant vulnerability rating (High, Moderate, Low) for Alton Wells 3/4 and Caledon Village Well 4 respectively. Figures 28 to 30 illustrate the SWAT vulnerability scores within the Alton 3/4 25-year WHPA TOT. The scoring was conducted for general contaminants (Figure 28), pathogens (Figure 29), and DNAPLs (Figure 30) as per Table 4.1 in MOE's Guideline, and outlined in Table 1 of this report. Similarly, the SWAT times and intrinsic vulnerability rating for Caledon Village well 4 are illustrated on Figures 31 to 33.

Within the Alton 3/4 area, the vulnerability rating within the 25-year WHPA TOT (Zone D) is primarily low, leading to vulnerability scores of 2 outside the 5-year WHPA TOT (Figures 28 to 30). There were no SWAT areas with travel times less than 5 years, and as such the vulnerability scores outside Zone A are scored less than 10 for the general contaminants (Figure 28).

Within the Caledon Village Well 4 area, the intrinsic vulnerability scores for the general contaminants within the 25-year WHPA TOT (Figure 31) range from 10 in the 100 m fixed radius zone (Zone A), to scores of 8 and 6 within the 2 year WHPA TOT zone, and scores of 6 and 2 outside the 2 year WHPA TOT zone. Figures 32 and 33 illustrate the vulnerability scores for DNAPLs and Pathogens respectively.

3.1.8 Summary –Alton 3/4 and Caledon Village 4

In general, the SWAT analysis results are somewhat consistent with chemistry observations and help to better understand the groundwater flow system surrounding the wellfields. The SWAT times and vulnerability scoring results differ from the ISI results (AquaResource, 2007) in the Alton area as the ISI was completed on the uppermost unconfined aquifer, while the SWAT results reflect the vulnerability of deeper flow zones which are simulated to be captured by the well. The ISI analysis was not able to represent the influence of the underlying flow system in this regional flow setting, however it is considered to be more conservative as it is protective of the shallow aquifer system overlying the capture zone.

3.2 Caledon Village Well 3

3.2.1 Hydrostratigraphy

Hydrostratigraphy in the area of Caledon Village Well 3 is dominated by coarse-grained sediments associated with the Caledon Meltwater Channel, and the highly transmissive underlying Amabel Formation bedrock (Figure 10; AquaResource, 2007). Caledon Village Well 3 intersects a thick unconfined surficial aquifer associated with the Caledon Meltwater Channel, and the well extends to a depth of approximately 37 m below ground surface. North of the wells outside the Caledon Meltwater Channel, the overburden thins significantly and sandy silt tills associated with the Port Stanley Till Plain and the

Singhampton Moraine predominate (Cross-sections in Appendix A; AquaResource, 2007).

3.2.2 Groundwater Flow System

Groundwater flow in the vicinity of the Caledon Village Well 3 capture zone extends from the north, towards the sand and gravel deposits of the Caledon Meltwater Channel (Figures 18-21, AquaResource, 2007). Groundwater flow in the shallow overburden extends from the recharge areas north of Caledon and is influenced by the Caledon Meltwater Channel and the presence of the man-made ponds associated with active, below watertable aggregate extraction. Groundwater flow in the deep groundwater system is from the north also and trends toward the Credit River and the crest of the Niagara Escarpment. Groundwater captured by these wells is recharged locally; this is indicated in that the 25-year capture zone and the 10-year capture zone are almost coincident (Figure 28; AquaResource, 2007).

A more detailed discussion of the capture zone is contained within the Region of Peel WHPA Study (AquaResource, 2007).

3.2.3 UZAT/SAAT

The shallow unconfined hydrostratigraphic setting and the lack of an overlying aquitard results in relatively low UZAT values (see Figure 34 for histogram). The UZAT within the 25-year capture zone for Caledon Village Well 3 ranges from longer times of approximately 5 years (located south and down-gradient of the wellfield) to travel times of 0 years for points located within discharge zones or within the ponds associated with the neighbouring gravel pits (Figure 35).

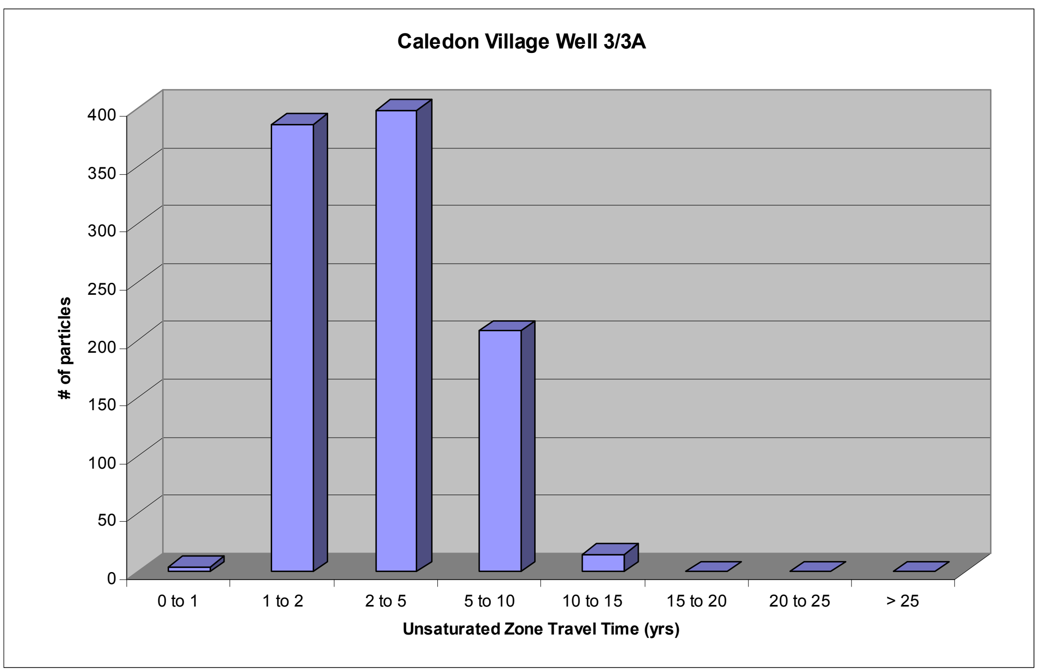

Figure 34: Histogram of the Unsaturated Zone Advection Travel Time for Caledon Village Well 3

These low travel times indicate the unsaturated zone in the area is relatively thin. The UZAT times for Caledon Village Well 3 are considerably shorter than the UZATs calculated for Alton Wells 3/4 and Caledon Village Well 4. Part of the area in the immediate vicinity of the Caledon Village Well 3 has UZAT times longer than 5 years, and this area corresponds to an increase in ground surface elevation associated with an increased thickness in the sand aquifer at surface. This increased thickness translates to a greater depth to watertable in the area, and therefore a longer UZAT travel time. The same zone is mapped as a medium vulnerability in the ISI vulnerability mapping in AquaResource (2007), whereas the remainder of the wellfield was mapped as high intrinsic vulnerability. Consequently the ISI and UZAT evaluations suggest similar results.

As the municipal well is completed in an unconfined aquifer, the top of the municipal aquifer for this wellfield is considered to be the watertable position. As a result, the Surface to Aquifer Advection Times (SAAT) within the 25-year WHPA TOT capture zone are coincident with the UZAT values. The majority of the 25-year capture zone area is simulated to have unsaturated travel times less than 5 years, and this type of low attenuation capacity within the unsaturated zone is expected at this location due to the coarse-grained nature of the surficial materials.

3.2.4 WWAT

The distribution of travel times within the saturated zone (watertable to well) for Caledon Village Well 3 are illustrated on Figure 36. Although the saturated travel times ranged from 5 years to 75 years, the majority of travel times are less than 20 years. Comparing this analysis with the WWAT results in Alton 3/4 and Caledon Village Well 4 area, the recharge area for Caledon Village Well 3 is considered to be relatively local with shorter advective travel times (Figure 37).

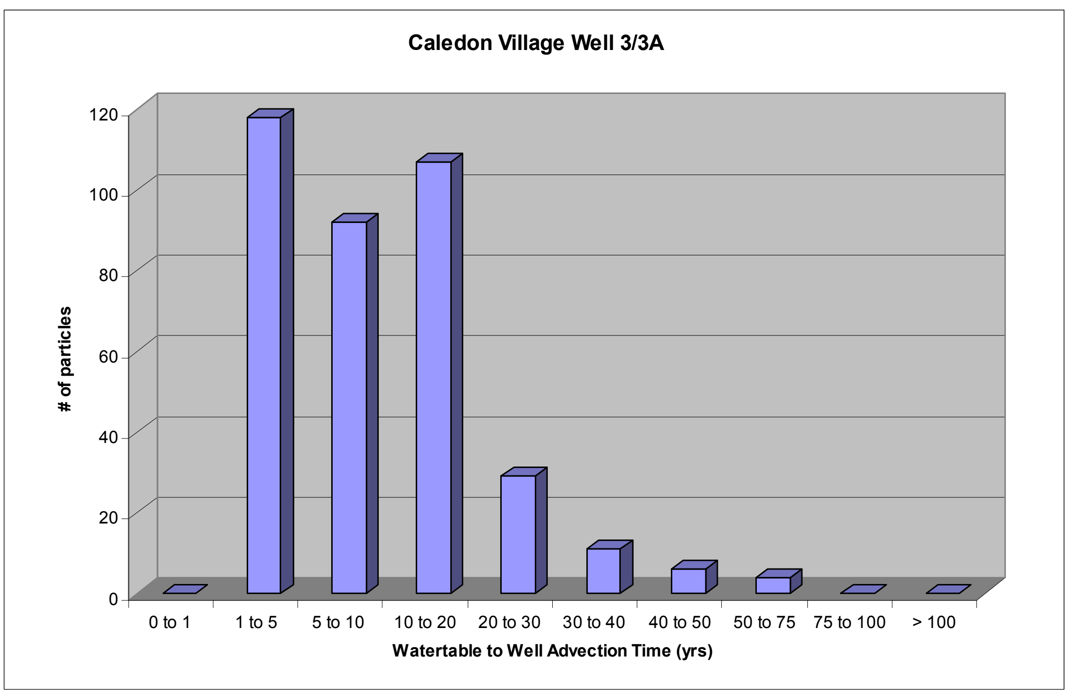

Figure 36: Histogram of Watertable to Well Advection Travel Time for Caledon Well 3

Figure 37 illustrates the WWAT times for particles that extend from the watertable to Caledon Village Well 3, and the resultant WWAT vulnerability rating (high, medium, low). In general, the WWAT vulnerability is high (0- 5 years) in the area surrounding the well, and increases with distance from the municipal well.

3.2.5 Intrinsic Vulnerability Scoring – WWAT – Caledon Village Well 3

Figures 38 to 40 illustrate the WWAT vulnerability scores within the Caledon Village Well 3 WHPA TOT zones. The scoring was conducted for three classes of contaminants: general contaminants (Figure 38), DNAPLs (Figure 39), and Pathogens (Figure 40) as per Table 4.1 in MOE's Guideline, and outlined in Table 1 of this report.

The vulnerability score within the 'Zone of Prohibition' (Zone A) is mapped as 10 irrespective of the vulnerability rating (Figure 38 to 40), and Zone C (2 to 5 year) is similarly mapped as a 10 for DNAPLs (Figure 39). The vulnerability scores for general contaminants range from 10 to 8 within the 2-year WHPA TOT (Zone B) and from 8 to 2 within Zones C and D (Figure 38).

3.2.6 SWAT

The surface to well advection time for particles released within the 25-year capture zone for Caledon Village Well 3 were computed as the summation of the unsaturated zone and the saturated zone travel times (UZAT + WWAT). Where the capture zone is located at a significant depth beneath the watertable and/or ground surface, the SWAT can be considerably higher than the capture zone travel time. As a result, the SWAT provides insight into the level of well vulnerability.

Figure 41 presents a histogram of the SWAT particles for Caledon Village Well 3. As this histogram indicates, the majority of the particles travel from ground surface to the well within approximately 20 years (only marginally more than the WWAT values). This calculation is consistent with the expected high intrinsic vulnerability of this unconfined aquifer; all recharge for the wellfield is local and there is limited protection against any potential contamination entering the municipal aquifer within the capture zone.

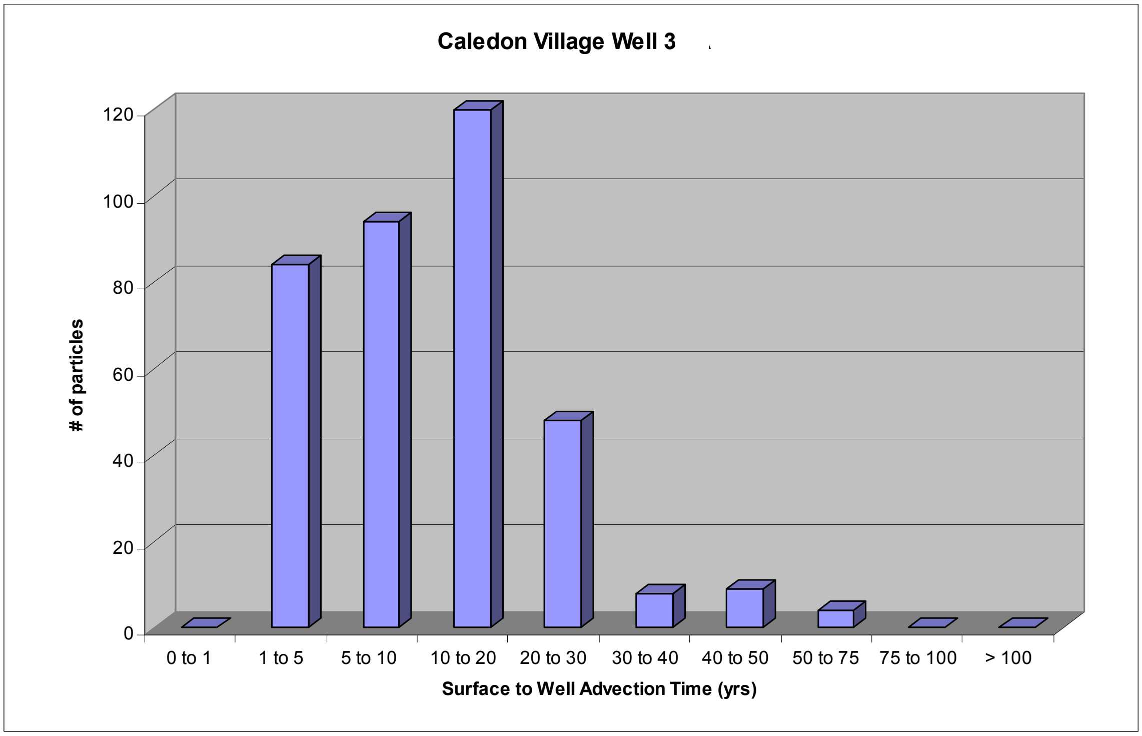

Figure 41: Histogram of Surface to Well Advection Travel Time for Caledon Wells 3.

The water quality within the municipal well is good considering the vulnerability and relatively low SWAT values. Concentrations of chloride, nitrate and sodium reported in Peel's Early Warning Wells are generally low to moderate, however monitoring wells screened in the shallow sands and gravels (e.g. EW 3-3s) exhibit higher chloride concentrations (119-134 mg/L in 2005) than wells screened at greater depths (e.g. EW 3-3d; 8 mg/L to < 60 mg/L; Beatty, 2005), and the chloride concentrations appeared to be increasing since 1998 (Stantec, 2002). Tritium analysis (Stantec, 2002) estimated the age of the water at less than 30 years, which is within the range calculated as part of the SWAT analysis.

Figure 42 presents a map of the SWAT particle times and the resultant SWAT vulnerability rating for Caledon Village Well 3. The area just north of the well and extending north to Caledon Creek have SWAT values that range from 0 to 5 years (high vulnerability rating). SWAT times that range from 5 to 25-years encompass the area north of Caledon Creek into Caledon Village, and this zone is very similar in extent to the 25-year capture zone indicating the lack of confining layer (and thick unsaturated zone) within this area.

3.2.7 Intrinsic Vulnerability Scoring – SWAT – Caledon Village 3

Figures 43 to 45 illustrate the SWAT vulnerability scores within the 25-year WHPA TOT zones. The scoring was conducted for three classes of contaminants: general contaminants (Figure 43), DNAPLs (Figure 44) and Pathogens (Figure 45) as per Table 4.1 in MOE's Guideline, and outlined in Table 1 of this report.

Caledon Village Well 3 is completed in a shallow unconfined aquifer, and as Figure 42 illustrates, the vulnerability mapping within the SWAT zones is predominately high to moderate throughout the 25-year WHPA TOT. As such, the vulnerability scores are elevated as well. The vulnerability score within the 'Zone of Prohibition' (Zone A) is mapped as 10 irrespective of the vulnerability rating for all contaminants of concern, and Zone C (2 to 5-year) is also mapped as a 10 for DNAPLs (Figure 45). The scores for general contaminants are 10 and 8 within 2-year WHPA TOT and mostly 6 outside the 2-year TOT.

3.2.8 Summary – Caledon Village 3

With the relatively homogeneous conditions surrounding the Caledon Village Well 3, the SWAT analysis appears to have produced results that are consistent with the field observations and our understanding of the geology and hydrogeology of the Caledon Village Well 3 area.

3.3 Inglewood Wells 1/2 and Well 3

3.3.1 Hydrostratigraphy

The Village of Inglewood has three municipal wells; Well 1 (not in use), and Well 2 located 10 m from Well 1 on the west side of the Credit River, and Well 3 located east of the Credit River. Inglewood Wells 1 and 2 are shallow wells (screened 6 to 10 m below ground surface) completed in a shallow sand and gravel aquifer, and there is a thin low permeability unit overlying the production aquifer, however the aquifer is described as leaky confined to unconfined (AMEC, 2000a). Inglewood Well 3 is a deep well screened approximately 50 m below ground surface which intersects a sand and gravel layer near the base of a buried bedrock valley, and this well is reported to be confined to semi-confined. More detailed information on the well setting is provided in Figure 11 and Appendix A of AquaResource, 2007.

3.3.2 Groundwater Flow System

Groundwater flow in the vicinity of the Inglewood Wells 1/2 is toward the Credit River from both the east and west sides (Figure 18, AquaResource, 2007). Inglewood Wells 1/2 lie near the Credit River and therefore, their capture zones follow the local groundwater gradients and extend outwards in a westerly and easterly direction from the wellfield. The capture zone for Inglewood Well 3 extends in a northerly direction beneath Highway 10, in the direction of the local groundwater flow gradients (Figure 29; AquaResource, 2007).

3.3.3 UZAT

As noted above, Inglewood Wells 1/2 are completed in a shallow aquifer that is considered to be unconfined, and therefore the UZAT for these twinned wells is considered to be coincident to the SAAT. Inglewood Well 3 is considered to be completed in a confined aquifer and therefore, the UZAT will not be equivalent to the SAAT, and is discussed separately below.

A histogram of the UZAT calculations conducted within the 25-year time of travel capture zone of the Inglewood 1/2 wells are illustrated on Figure 46, and for Inglewood Well 3 on Figure 47. Figure 46 illustrates that there is a wide variation and range in unsaturated zone travel times within the 25-year capture zone for these wells. The till-rich upland areas that flank the valley sediments are predicted to have significantly longer travel times than in other capture zone areas (c.f. histograms for Caledon Village wells, Figures 15 and 34).

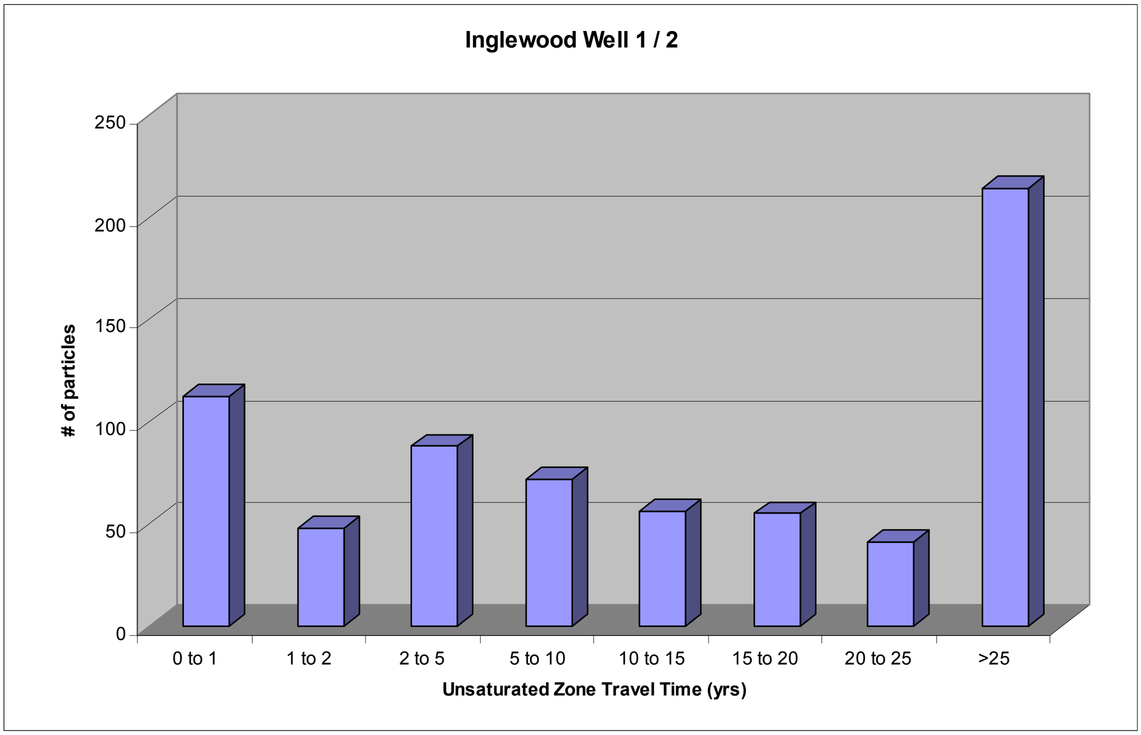

Figure 46: Histogram of the Unsaturated Zone Advection Time for Inglewood Wells 1/2

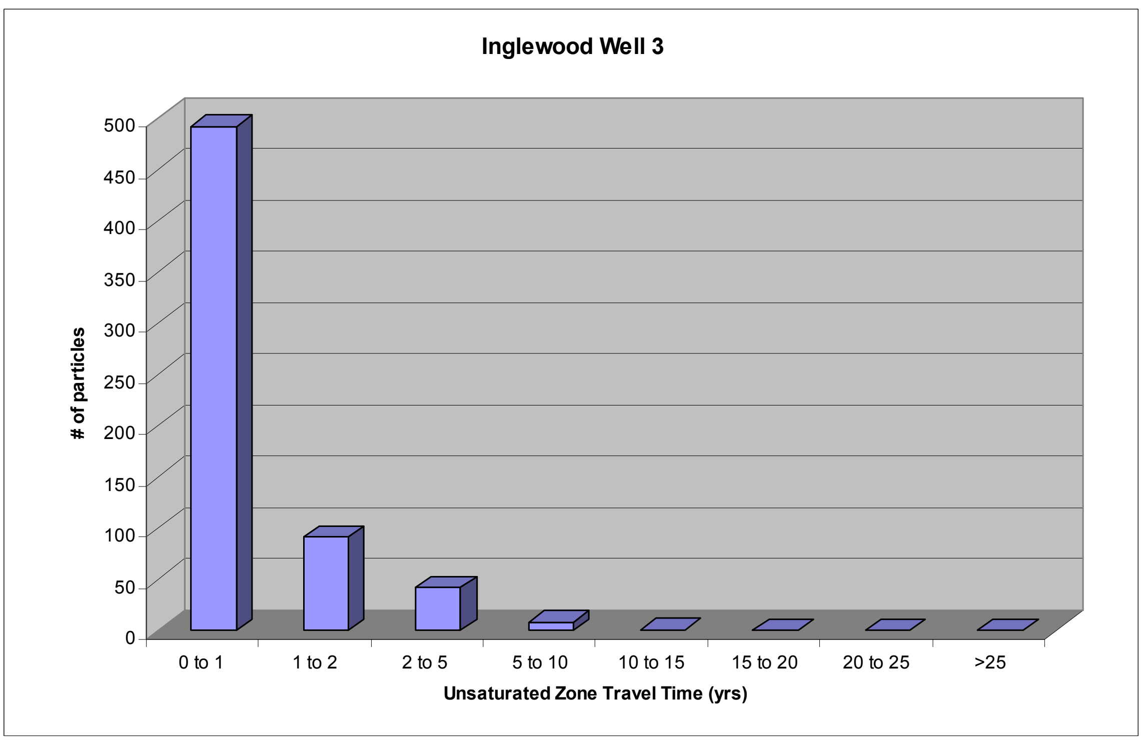

Figure 47: Histogram of the Unsaturated Zone Advection Time for Inglewood Well 3

Figure 48 presents a plan view of the unsaturated zone travel times computed for particles released within the 25-year capture zone of Inglewood Wells 1/2. This figure clearly illustrates that the areas surrounding the Credit River and the floodplain have very shallow watertable conditions, and low (< 2 year) unsaturated zone advective travel times. These travel times are considered reasonable as the municipal wells lie within the topographically depressed Credit River floodplain, where coarse-grained outwash and alluvial sediments are mapped at ground surface (Figure 11; AquaResource, 2007).

The coarse-grained overburden sediments and the high watertable produce the low UZAT calculations in the floodplain area that surrounds the wells. Outside the floodplain, fine-grained till is mapped on the flanks of the river valley and the Escarpment rise (Karrow, 1991). Review of Inglewood cross-section C-C' from the Region of Peel WHPA Study (AquaResource, 2007; Appendix A) illustrates an area of thick clay till on the flanks of the Credit River valley. The increased depth to watertable, low recharge and clay-rich tills outside the river valley produce the higher UZAT calculations (i.e. longer travel times) for this area.

The unsaturated zone advection times calculated for Inglewood Well 3 are also relatively low (i.e. indicative of shorter travel times), in the area surrounding the well with over 90% of the recharge particles having UZATs of less than 2 years within the 25-year capture zone (histogram - Figure 47). These calculations are considered reasonable as the area lies at the base of the Niagara Escarpment where the topography is fairly low lying, and there are several nearby surface water discharge features, including 3 ponds, the Credit River and some small tributaries.

A plan-view map of the unsaturated zone advection times calculated for Inglewood Well 3 is presented in Figure 49. The majority of UZAT values correspond to travel times of less than 2 years (red dots; Figure 49). The blank areas in this figure where particles are not illustrated are areas of groundwater discharge (as predicted by the groundwater model). These discharge areas have unsaturated travel times equal to zero, as the watertable is predicted by the model to lie at ground surface.

3.3.4 SAAT

The surface to aquifer advection times (SAAT) within the 25-year capture zone for Inglewood Well 3 differs from the UZAT because the municipal well is completed in a confined aquifer. Figure 50 presents a map of the calculated SAAT times for particles that travel from the surface to the top of the municipal aquifer, and also the SAAT vulnerability rating (high, medium, low). As noted above, there are areas where the particles are not illustrated on the map, and these correspond to areas where the watertable is predicted to lie at ground surface, or where the particles traveled to a local discharge feature rather than the municipal well.

For those particles that reach the aquifer, the SAAT ranges from a minimum of 6 years to a maximum of 47 years. As the minimum advective time of travel from ground surface to the aquifer is greater than 5 years, there are no high vulnerability areas (SAAT times from 0-5 years) for Inglewood Well 3. The medium vulnerability area (SAAT times ranging from 5 to 25-years) encompass the central portion of the capture zone, extending northwest to The Grange Sideroad. As noted above, the calculated UZAT values for this well were low (i.e. short travel times), and the majority of the travel time estimated to reach the municipal aquifer is saturated travel time.

The SAAT times are calculated from the ground surface to the top of the municipal aquifer. When the aquifer is deeply buried and confined, and there are multiple aquifers present, particles released on the ground surface have the potential to travel within the surficial aquifer either towards more distant topographic lows, or to surface water features. In the vicinity of Inglewood Well 3, there are several local ponds and tributaries that are predicted by the groundwater model to receive local recharge. There are some particles which bypass a local aquitard which underlies Highway 10 (see cross-section F-F' in AquaResource, 2007), and these particles reach the underlying aquifer and travel within the confined aquifer to the municipal well.

3.3.5 WWAT

The watertable to well advection time (WWAT) for the particles captured within the 25-year capture zone of Inglewood Wells 1/2 had a full range of travel times from 1 year to greater than 100 years (Figure 51). This broad range of values reflects the distribution of materials within the capture zone, which vary from coarse grained fluvial deposits in the Credit River valley to Halton Till (with interbedded sands) along the floodplain and upland areas.

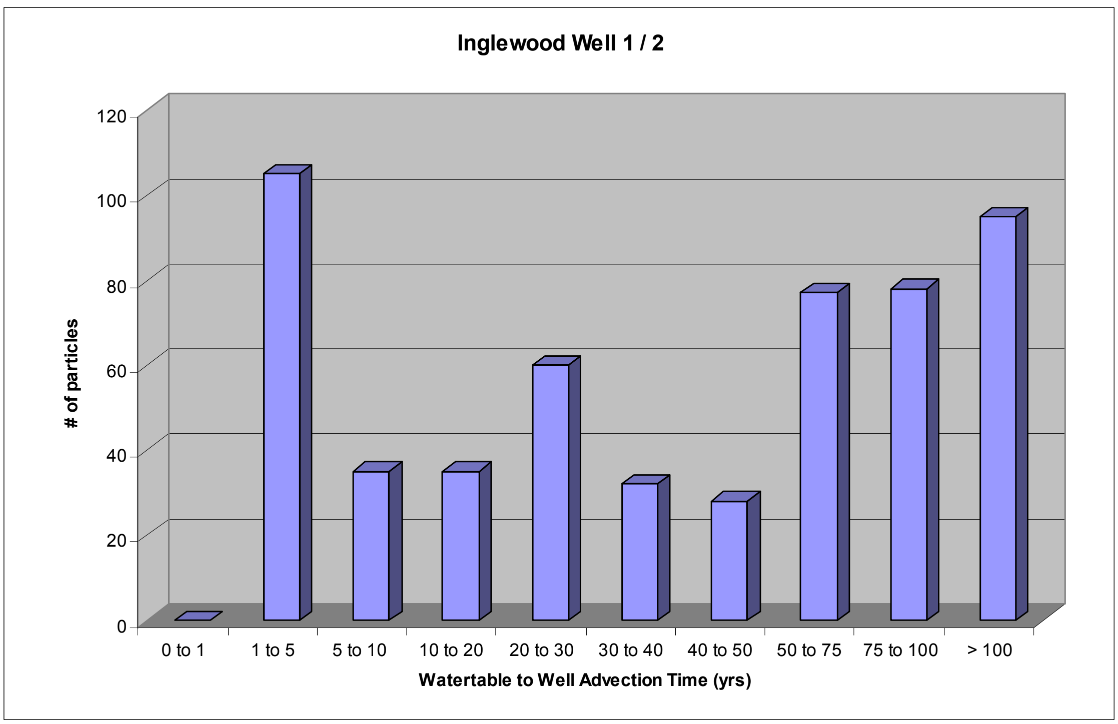

Figure 51: Histogram of Watertable to Well Advection Time for Inglewood Wells 1/2.

In contrast, the WWAT values computed for Inglewood Well 3 range predominately from 5 to 30 years, as illustrated in Figure 52. Comparison of Figures 51 and 52 shows that there is a lack of short-duration (< 5 year) particle traces within the Inglewood Well 3 area, which reflects the confined nature of the well. The lack of long (>50 year) WWAT values at Inglewood Well 3 suggests that the hydrogeologic conditions in the 25-year capture zone are more uniform than those surrounding Inglewood Wells 1/2.

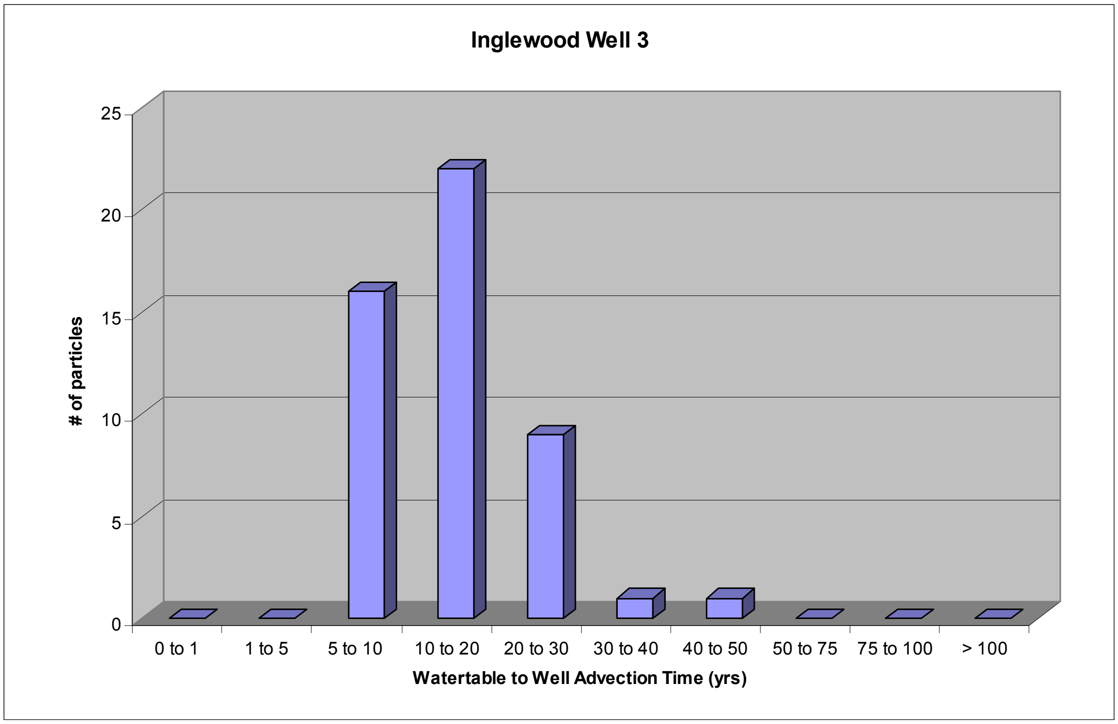

Figure 52: Histogram of Watertable to Well Advection Time for Inglewood Well 3.

Figure 53 illustrates the WWAT times and resultant vulnerability rating for Inglewood Wells 1/2. The high vulnerability areas (0 to 5 year WWAT times) lie primarily in the low lying areas on either side of the Credit River. The moderate vulnerability areas (5 to 25-year) surround the high vulnerability areas to the west and east, and the low vulnerability areas extends on the far east and west portions of the 25-year time of travel capture zone.

Figure 54 illustrates the WWAT times and resultant vulnerability rating for Inglewood Well 3. As there are no particles within the analysis with a WWAT travel time less than 5-years, there are no high vulnerability zones mapped in the 25-year capture zone for Inglewood Well 3. Moderate vulnerability (WWAT times of 5 to 25-years) are delineated by relatively few particles that lie in the central portion of the 25-year time of travel capture zone, and low vulnerability zones (WWAT times greater than 25 years) are mapped in another small portion of the 25-year capture zone.

3.3.6 Intrinsic Vulnerability Scoring – WWAT - Inglewood Wells

Figures 55 to 57 illustrate the WWAT vulnerability scores within the Inglewood 1/2 time of travel capture zones, and Figures 58 to 60 illustrate the WWAT scores within the Inglewood Well 3 capture zones. The scoring was conducted for three classes of contaminants: general contaminants, pathogens, and DNAPLs as per Table 4.1 in MOE's Guideline, and outlined in Table 1 of this report.

Inglewood Wells 1/2 are completed in a shallow unconfined aquifer, and as Figure 55 illustrates, the WWAT vulnerability scores are elevated (10 to 8) throughout much of the central portion of the capture zone near the municipal wells. The vulnerability scores decrease (ranging from 8 to 2) with increasing distances west and east of the municipal wells. Inglewood Well 3 is completed in a confined system, and as such the majority of the recharge for this system occurs outside the 25-year capture zone. As such, there were few particles predicted by the model to travel from the ground surface to the municipal well, and as such the polygons that make up the high, moderate and low vulnerability ratings (Figure 54) are small compared to the 25-year capture zone. The vulnerability scores (Figure 58 to 60) range from 10 (Zone A) to 2 depending on the contaminant of concern.

3.3.7 SWAT

Figures 61 and 62 are histograms illustrating the SWAT values for particles released on the surface and reaching the Inglewood Wells 1/2 and 3 municipal wells.

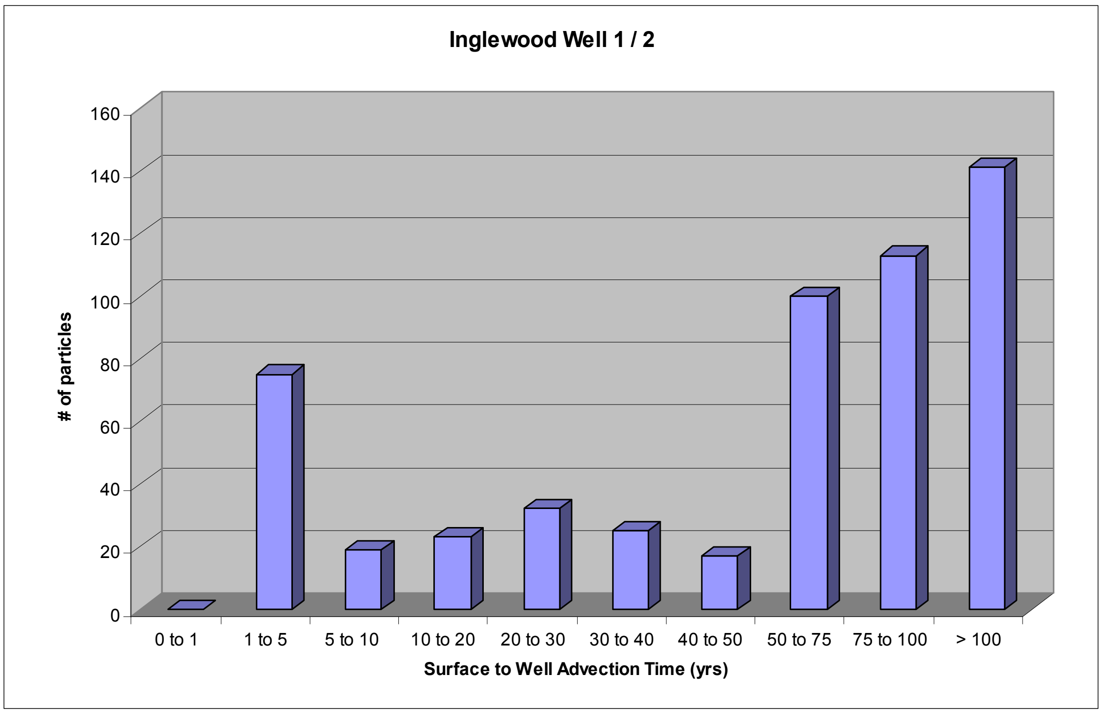

Figure 61: Histogram of the Surface to Well Advection Time for Inglewood Wells 1/2

Figure 61 illustrates a wide variation in the SWAT values for Inglewood Wells 1/2. Similar to the WWAT particles presented on Figure 51, the particles released near the municipal wells resulted in relatively short SWAT values (less than 5 years), however many of the particles released within the 25-year capture zone that are captured by the wells have SWAT values greater than 50 years.

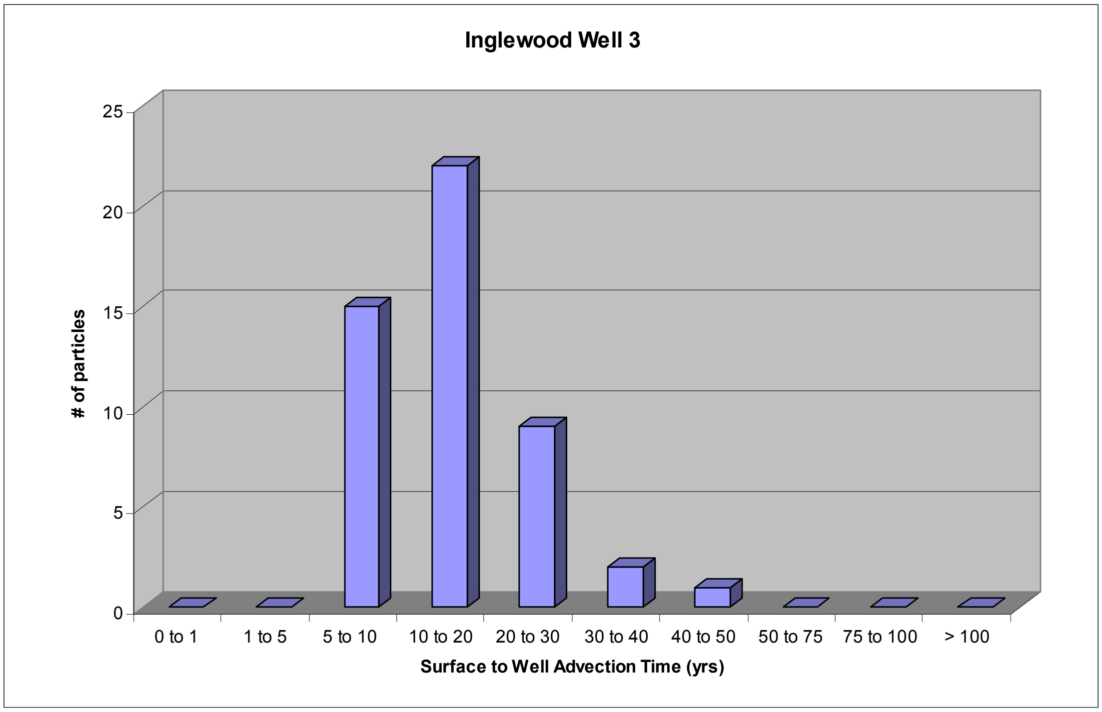

Figure 62: Histogram of the Surface to Well Advection Time for Inglewood Well 3

Figure 63 presents a plan-view map of the SWAT times and resulting vulnerability rating (high, medium, low) for Inglewood Wells 1/2. The SWAT values calculated for this wellfield reflect those presented for the UZAT and WWAT described earlier (Figures 48 and 53). Similar to the WWAT zones, the high vulnerability SWAT areas (0 to 5-year WWAT times) surround the Credit River and the valley floodplain. The 5 to 25-year SWAT times (moderate vulnerability) encompass an area that is smaller than the comparable WWAT zone, due to the high UZAT values on the western and eastern portions of the 25-year TOT capture zone.

Figure 64 presents the SWAT times and vulnerability rating for Inglewood Well 3. As noted above in the WWAT discussion, there are no SWAT particles that travel from the surface to the well in less than 5 years, and therefore high vulnerability areas do not exist within the Inglewood Well 3 capture zone. The SWAT vulnerability rating therefore is mapped as moderate to low within the 25-year time of travel capture zone (Figure 64).

Inglewood Well 3 is screened deep below the ground surface, and its depth and high UZAT and WWAT travel times help decrease the SWAT vulnerability of the municipal aquifer in this area.

3.3.8 Intrinsic Vulnerability Scoring – SWAT - Inglewood Wells

Figures 65 to 67 illustrate the SWAT vulnerability scores within the Inglewood 1/2 capture zones, and Figures 68 to 70 illustrate the SWAT scores within the Inglewood Well 3 capture zones. The scoring was conducted for three classes of contaminants: general contaminants, pathogens, and DNAPLs as per Table 4.1 in MOE's Guideline, and outlined in Table 1 of this report.

3.3.9 Summary – Inglewood 1/2 and 3

The SWAT analysis for Inglewood Wells 1/2 are consistent with the ISI based intrinsic vulnerability mapping conducted previously (AquaResource, 2007). There is little water quality information available for the Inglewood Early Warning Wells as they were dry when Beatty (2005) conducted their annual sampling. Additional information provided by Peel in early 2008 indicated that chloride and sodium concentrations were 73 mg/L and 104 mg/L respectively in the spring of 2006 (Beatty, 2006). Both concentrations are above the background levels and indicate some impact to shallow aquifer from road salting in the Inglewood 1/2 area.

Water quality information from the Region of Peel and reported by CVC (CVC, 2006) shows that nitrates in Wells 1/2 are generally low (less than 1 mg/L), however concentrations of sodium and chloride have been rising over the last 20 years, and are currently at moderate levels (approximately 30 mg/L and 65 mg/L respectively). These chemistry results do not reflect the inferred low SWAT travel times calculated for the area within the Credit River valley; however the mixture of the local recharge with the more distant recharge may be what results in the generally good water quality observed at this well pair. There are few water wells located in the area surrounding the Credit River and the floodplain and as such there is a degree of uncertainty associated with the protective layers that may overlie the municipal wells. Given the proximity to the Credit River, the watertable in this area is interpreted to be high, and UZAT times therefore are likely to be low. However, given the nature of the Credit River as a regional discharge zone, the model may be overpredicting the contribution of the local groundwater flow system and underpredicting the contribution of the regional groundwater flow captured by the wells.

The SAAT and SWAT analysis for Inglewood Well 3 is consistent with the earlier intrinsic vulnerability assessment, which indicated that the majority of the area has a moderate to low vulnerability. Further, the water quality data from Inglewood Well 3 and the Early Warning Wells in the area show that water quality is very good, which is also consistent with the WWAT and SWAT analysis.

3.4 Cheltenham Wells PW1/PW2

3.4.1 Hydrostratigraphy

The Village of Cheltenham is serviced by a pair of municipal wells, located adjacent to the community fire hall. In the Cheltenham area, overburden ranges in thickness from a few metres along the Niagara Escarpment to over 50 m. Cheltenham PW1/ PW2 lies on the east side of the Credit River, just east of the Escarpment. Cheltenham Wells PW1/ PW2 are relatively deep wells (screened approximately 40m below ground surface) and are located less than 10 m from one another. These wells are completed in a confined sand and gravel aquifer, which is overlain by approximately 10 m of Halton Till. Overburden in the area is dominated by the fine-grained clay-rich Halton Till, which in the Cheltenham area contains interbeds of sands with lesser gravels (Figure 12 and Appendix A; AquaResource, 2007).

3.4.2 Groundwater Flow System

Groundwater flow in the vicinity of the Cheltenham wells is toward the Credit River from the southeast (Figures 18-21; AquaResource, 2007). Cheltenham Wells PW1/PW2 are confined by the overlying Halton Till and thus primarily capture regional groundwater flow heading toward the Credit River. The 25-year capture zone for Cheltenham Wells PW1/PW2 extends in a southeasterly direction beneath King Sideroad (RR9) (Figure 30; AquaResource, 2007).

3.4.3 UZAT/ SAAT

As the Cheltenham PW1/PW2 wells are completed in a confined aquifer, SAAT values were calculated by summing the UZAT values with the watertable to aquifer advection time (WAAT) values.

The UZAT values calculated within the 25-year capture zone range from less than 1 year to over 40 years, with an average of 14 years (Figure 71). The low mobile moisture content assumed for the Halton Till, as well as the modest depth to watertable in the area tend to skew the dominant unsaturated zone travel times to higher values indicative of longer travel times. As a result, it is predicted that the Halton Till presents an effective reduction in the intrinsic vulnerability at this wellfield. As illustrated in Figure 71, the most common UZAT value within the 25-year time of travel capture zone is between 15 and 20 years.

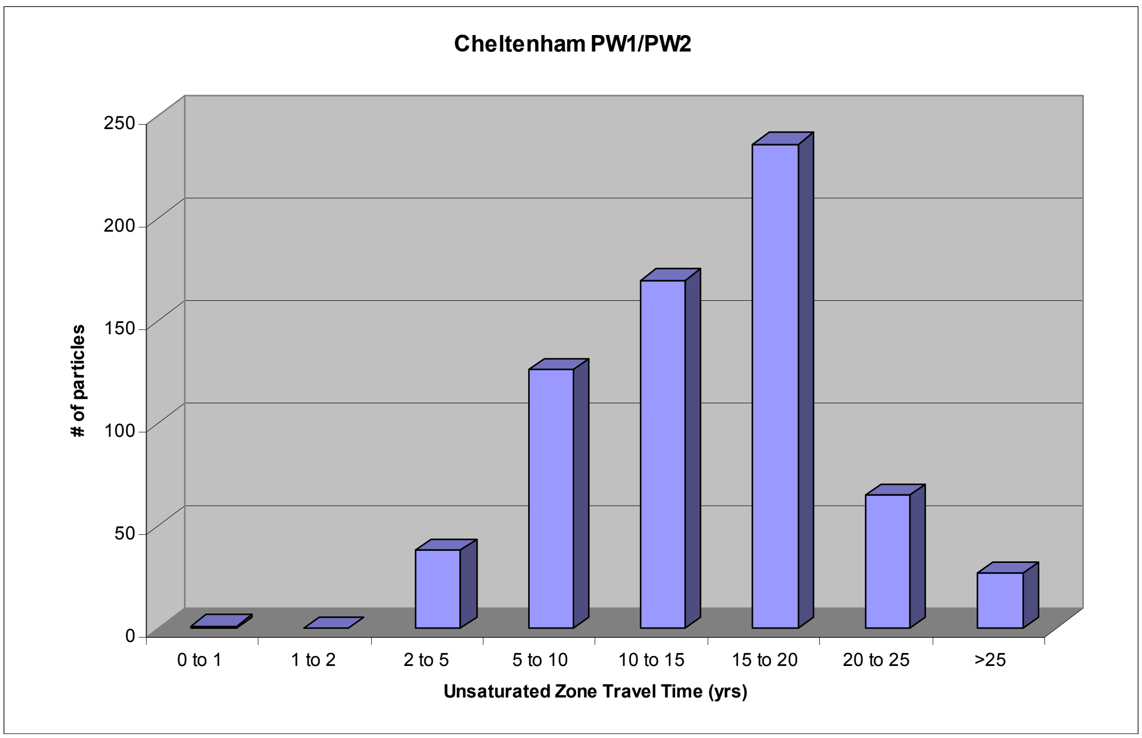

Figure 71: Histogram of Unsaturated Zone Advection Time for Cheltenham PW1/ PW2

Figure 72 illustrates the distribution of UZAT values within and surrounding the 25-year capture zone. As illustrated on this figure, the area in the eastern portion of the capture zone contains shorter UZATs due to the presence of a sand unit mapped at surface (Karrow, 1991). This sand layer is represented as a having a lower soil moisture content and higher recharge in the UZAT calculation, which produces the faster UZAT and SAAT times.

In general, the UZAT trend described above is consistent with the SAAT values calculated within the 25-year capture zone (See Figure 73). This figure contains colourcoded symbols representing the SAAT particle times as well as the resultant SAAT vulnerability rating, which ranges from medium to low as there were no SAAT travel times less than 5 years that would reach the aquifer. The SAAT travel times tend to be long in the area surrounding the well where the fine-grained till predominates (see Cheltenham cross-section A-A', Appendix A; AquaResource, 2007).

3.4.4 WWAT

The watertable to well advection time (WWAT) values were computed within the 25-year capture zone for the Cheltenham wellfield. The WWAT times for this wellfield (Figure 74) indicate a broad range of travel times from less than 5 years to over 100 years. However the majority of particles reached the wellfield in 10 to 30 years. Areas with WWAT times greater than 25-years reflect the slow advection time from the watertable to the underlying municipal aquifer through the clay-rich Halton Till. The wide range of predicted WWAT times, and the dominance of values in the 10 to 30-year range suggests that only a portion of the Halton Till is saturated.

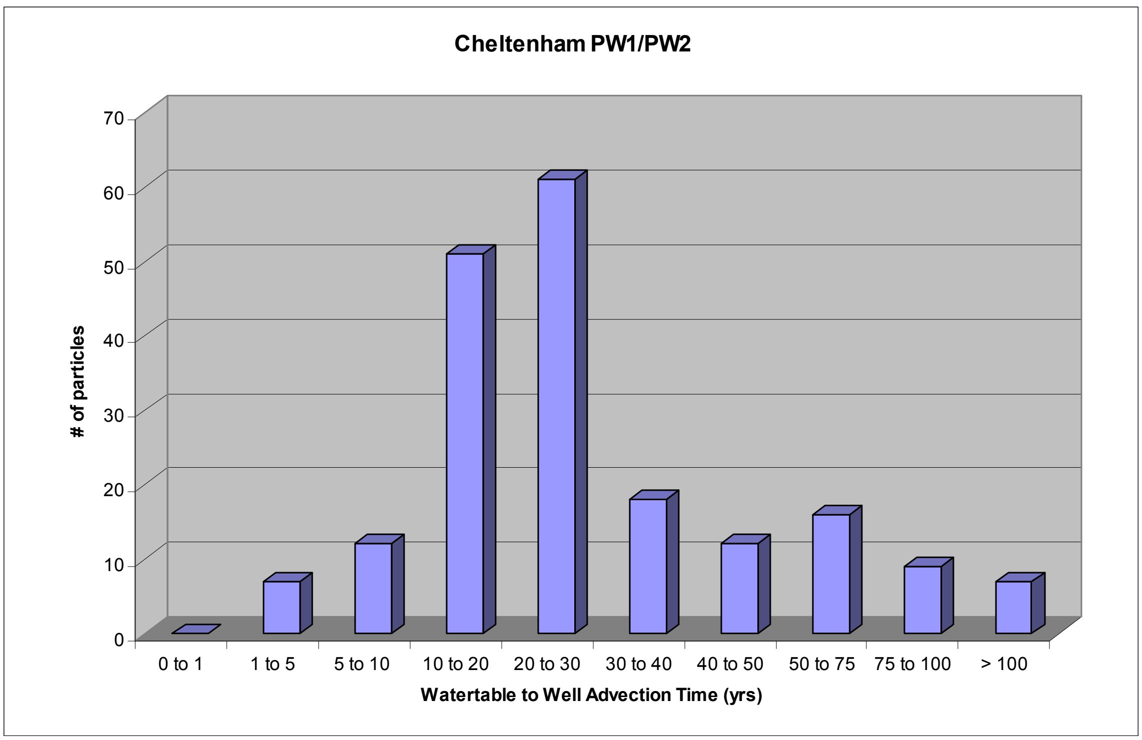

Figure 74: Histogram of the Watertable to Well Advection Time for Cheltenham PW1/ PW2

Figure 75 illustrates the WWAT times and vulnerability rating for the Cheltenham PW1/PW2 wellfield. Only a small area immediately east of the wellfield is mapped with a high WWAT vulnerability rating (WWAT times of 0 to 5 years). Moderate vulnerability is mapped over the majority of the 25-year capture zone east of the wellfield, and low WWAT vulnerability encompasses a significant portion of the remaining 25-year time of travel capture zone. Particles in 25-year capture zone that are not captured by the municipal wells are not illustrated as particles on the WWAT map (Figure 75).

3.4.5 Intrinsic Vulnerability Scoring – WWAT - Cheltenham Wells

Figures 76 to 78 illustrate the WWAT vulnerability scores within the 25-year capture zone for Cheltenham PW1/ PW2. The scoring was conducted for three classes of contaminants: general contaminants (Figure 76), DNAPLs (Figure 77), and Pathogens (Figure 78) as per Table 4.1 in MOE's Guideline, and outlined in Table 1 of this report.

3.4.6 SWAT

Figure 79 illustrates a histogram of the SWAT times calculated within the 25-year time of travel capture zone for the Cheltenham wells. The SWAT values calculated for Cheltenham PW1/ PW2 range from 17 years to over 100 years. As illustrated, the majority of the SWAT values were found to be between 30 and 75 years. Very few particles captured by the well had SWAT values less than 20 years, which is reflective of the confined nature of the wellfield.

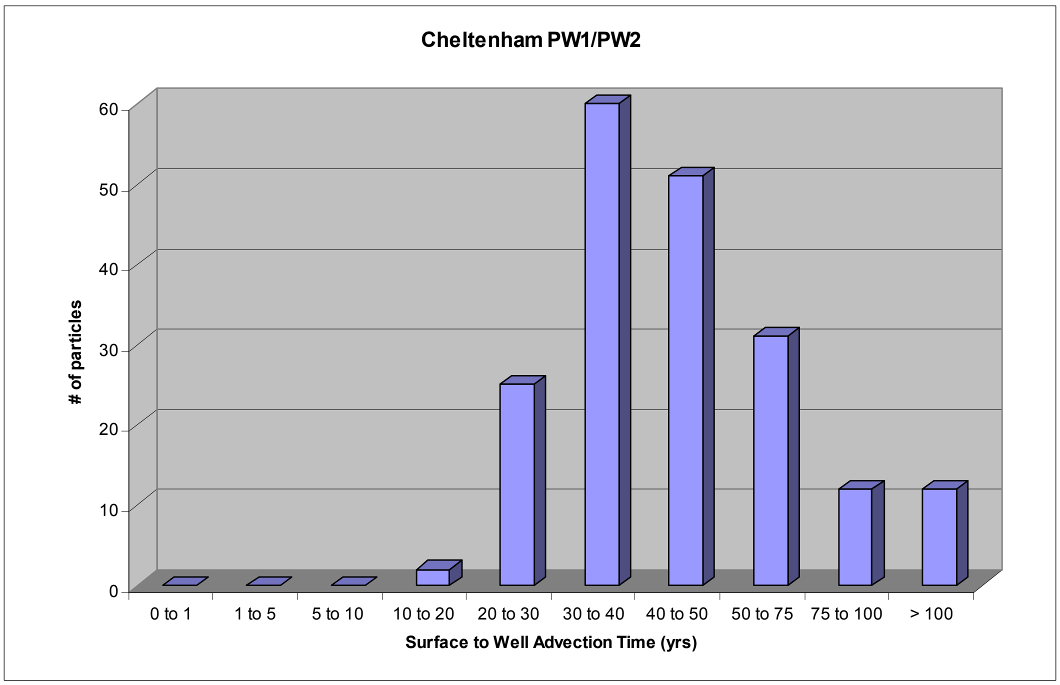

Figure 79: Histogram of Unsaturated Zone Advection Time for Cheltenham PW1/ PW2

A plan-view map of the SWAT times and the vulnerability rating for Cheltenham PW1/PW2 is illustrated on Figure 80. Cheltenham PW1/ PW2 is screened in a confined aquifer in a buried bedrock valley, and the depth to well contributes to the low vulnerability of the aquifer to surficial contaminants throughout the majority of the 25-year capture zone. As outlined in the WWAT discussion above, the particles in 25-year capture zone that are not captured by the municipal wells are not illustrated as particles on the SWAT map (Figure 80).

As there are no particles that extend from ground surface to the well in less than 5 years, there are no high vulnerability areas within the 25-year capture zone (Zone D), and there is only one small area immediately east of the wellfield delineated as medium vulnerability (SWAT times of 5 to 25 years).

3.4.7 Intrinsic Vulnerability Scoring – Cheltenham

Figures 81 to 83 illustrate the SWAT vulnerability scores within the Cheltenham capture zones. The scoring was conducted for three classes of contaminants: general contaminants (Figure 81), DNAPLs (Figure 82), and Pathogens (Figure 83) as per Table 4.1 in MOE's Guideline, and outlined in Table 1 of this report.

3.4.8 Summary – Cheltenham PW1/PW2

The SWAT analysis for Cheltenham Wells PW1/PW2 suggests a slightly lower intrinsic vulnerability than the ISI mapping completed earlier (AquaResource, 2007). This lower intrinsic vulnerability mapped using the SWAT method is consistent with available chemistry data; water quality in the Cheltenham wells is good with iron, manganese and sodium being the only exceedences of the Ontario Drinking Water Standards, and these exceedences are interpreted to be derived from the underlying shale bedrock as opposed to surficial sources of contamination.

3.5 Uncertainties in Vulnerability Mapping and Scoring

As noted earlier there are several contributing factors to the uncertainty associated with the vulnerability assessment. Those factors include uncertainty associated with the time of travel delineation and uncertainties associated with the vulnerability rating.

Uncertainty with the vulnerability rating is often due to uncertainty associated with the understanding and conceptualization of the hydrostratigraphic groundwater system. These uncertainties as well as uncertainties associated with the delineation of the UZAT, SWAT and WWAT times will be the focus of this discussion.

3.5.1 Alton 3/4

Uncertainty considerations relating the vulnerability assessment using advective travel time (SWAT/ WWAT) methods undertaken within the Alton capture zones are as follows:

- In the Alton capture zone, there are few wells within the 25-year time-of-travel capture zone (Zone D); therefore this zone was given a HIGH uncertainty value for the distribution of data and its quality.
- Results of the forward particle tracking show that very few particles reach the Alton 3/4 wells. In this regard there is poor confidence in the resulting SWAT and WWAT mapping, and as such the vulnerability assessment based on the advective travel time methods were given high uncertainty values.

3.5.2 Caledon Village

Uncertainty considerations relating to the vulnerability assessment using the SWAT/ WWAT methods within the Caledon Village Well 4 capture zones are as follows:

- The Caledon Village Well 4 capture zone is relatively small, however there are few data points (high quality water wells) within the 5 to 25-year capture zone.
- There is a high confidence in the hydrostratigraphic interpretations and in the modelling and therefore the reverse particle tracking for the capture zone delineations is considered to have a low uncertainty.
- The results of the forward particle tracking were fairly consistent with the conceptualization of the area and with the reverse particle tracking results, and

as such there is a low uncertainty with respect to the longer term SWAT/ WWAT travel times. The potential variability of the hydraulic conductivity of the municipal aquifer leads to a high uncertainty in terms of the 0 to 5 year WWAT and SWAT travel times and relating vulnerability mapping and ranking.

Uncertainty considerations relating to the vulnerability assessment using the SWAT/ WWAT methods within the Caledon Village Well 3 capture zones are as follows:

- Caledon Village Well 3/3A lies within an area that is known to contain significant quantities of coarse-grained sediment on top of bedrock. This understanding leads to a low level of uncertainty with respect to the conceptualization and capture zone delineations.
- The uncertainties in the long term SWAT travel times are low given the hydrostratigraphic understanding of the area, and the similarities between the reverse and forward particles tracks. However, the potential variability of the hydraulic conductivity of the municipal aquifer leads to a high uncertainty in the 0 to 5 year WWATs and SWATs and the resulting vulnerability mapping and ranking.

3.5.3 Inglewood

Uncertainty considerations relating to the vulnerability assessment using SWAT/ WWAT methods within the Inglewood 1/2 capture zones are as follows:

- The capture zones for Inglewood Well 1/2 extend beneath the Credit River to a location where the conceptual understanding of the depth to bedrock and infill sediments of the buried bedrock valley are poorly understood; this results in a higher uncertainty for the conceptualization. The conceptual model suggests the river may have eroded portions of the intermediate confining layer however additional boreholes would be needed to refine this understanding and lower the uncertainty associated with the capture zone delineation. There are only three wells within the 5-year time of travel capture zone, and therefore the distribution of data was assigned a high uncertainty.
- As the travel times obtained through forward and reverse particle tracking were similar, there was a low uncertainty applied to the 5 to 25 year, and > 25 year SWAT and WWAT time of travel zones, however, the potential variability of the hydraulic conductivity of the municipal aquifer leads to a high uncertainty in terms of the 0 to 5 year WWAT and SWAT travel times and the resulting vulnerability mapping and ranking.

Uncertainty considerations relating to the vulnerability assessment using SWAT/ WWAT methods within the Inglewood Well 3 capture zones are as follows:

- In the Inglewood Well 3 capture zone, there are few wells located at any distance from the municipal well. Therefore, the uncertainty associated with data distribution is considered high within the 5 to 25-year time-of-travel capture zone.
- Given the complexity of the capture zone area and it's proximity to the Escarpment and the confluence of the Credit River and East Credit River, the uncertainty associated with the conceptualization (based on the available data) is high. Additional boreholes drilled within the capture zone would reduce this uncertainty.

- There were very few particles that extended from the ground surface (or watertable) to the well, and as such there were few particles available for the forward particle tracking. As such there is a high uncertainty associated with the delineation of the SWAT/ WWAT travel times and the resulting relative vulnerability mapping and ranking.

3.5.4 Cheltenham

Uncertainty considerations relating to the SWAT/ WWAT methods within the Cheltenham PW1/ PW2 capture zones are as follows:

- The conceptual setting for this area is fairly well understood, although there is a poor understanding of the spatial and lateral continuity of sand lenses within the Halton Till, that may lead to higher than predicted travel times in the SWAT/ WWAT assessment. Therefore the uncertainty associated with the conceptualization is high.
- Given the uncertainty with the conceptualization, and the uncertainty associated with the hydraulic conductivity (within half an order of magnitude) of the municipal supply aquifer, the SWAT/ WWAT travel times and the resulting vulnerability mapping and ranking are considered to have a high uncertainty.

3.5.5 Summary of Uncertainty Rankings

The uncertainty ratings established above for the capture zones may be used in the Region of Peel's future Water Quality Risk Assessment as per the guidance documents (MOE, 2006). The uncertainty ranking, along with the risk assessment score, will be used to determine the need for (and spatial extent of) additional data collection and/or analysis. If the uncertainty is so high that there is not sufficient confidence in the assigned vulnerability scores to use them as a basis for prioritizing and developing risk management activities, then additional field data may be required prior to establishing the risk and assessing potential threats. This is considered to be the case within the Alton 3/4 capture zone, where it is recommended that additional data be collected within the 5-year capture zone to clarify the conceptual and numerical models.

The above analysis has shown that many of the vulnerability zones surrounding the municipal wells are lacking in data, primarily away from the municipal wells themselves. Thus this lack of data generally results in a high degree of uncertainty associated with the vulnerability mapping and ranking. Generally, the Region of Peel's early warning sentry wells are contained within Zone A and B and do not reduce the uncertainty in Zones C and D located further away from the wellfields.

4 SUMMARY

The Clean Water Act lays out a framework that aims to identify and assess the risks to the quantity and quality of municipal drinking water sources. The Act legislates that a series of studies be undertaken and the methodologies followed. The results of these studies will be assembled into an Assessment Report, which will form the basis of a Source Protection Plan that will outline how the municipalities in the Source Protection Region will address threats placed on the water supplies.

One of the studies legislated under the Clean Water Act by the Ontario Ministry of the Environment is the Groundwater Vulnerability Assessment. This assessment focuses on assessing the vulnerability of groundwater based water supplies to surficial sources of contamination. The Groundwater Vulnerability Assessment includes the mapping and ranking of the calculated vulnerability of the groundwater resources, and subsequently the vulnerability scoring. These outputs are then used as inputs into the Water Quality Risk Assessment.

Groundwater Vulnerability Assessments can be undertaken using a variety of approaches including mapping of the surficial vulnerability with the intrinsic susceptibility index method within the Time of Travel (TOT) capture zones (as outlined in AquaResource, 2007) or mapping the vulnerability using Surface to Well Advection Time (SWAT), or Surface to Aquifer Advection Times (SAAT). Vulnerability mapping and ranking using the SWAT and Watertable to Well Advection Time (WWAT) methods and their resultant scores were the focus of this vulnerability assessment.

Surface to well advection times (SWAT values) were calculated for the wellfields in Alton (3/4), Caledon Village, Inglewood and Cheltenham within the Region of Peel. The SWAT times were calculated to verify the vulnerability assessment completed previously (AquaResource, 2007). Peel Region may choose to apply different vulnerability approaches or methodologies in their Water Quality Risk Assessment stage(s).

SWAT values were calculated by summing the travel time through the unsaturated zone from ground surface to the watertable (UZAT), and the saturated travel time from the watertable to the well (WWAT). Forward particle tracking in the FEFLOW model was used to determine the saturated zone travel time (WWAT), while the unsaturated zone travel times (UZAT) were calculated independently within a GIS. UZAT values were calculated using modeled recharge rates, estimates of mobile water content and the thickness of the unsaturated zone. These two components of the travel time were combined to calculate the overall SWAT for each of the wellfields examined.

In a similar fashion, surface to aquifer advection time (SAAT) values were calculated for the 25-year Peel WHPA zones. Where unconfined conditions exist, the SAAT values are equivalent to the UZAT values. Where confined conditions exist, the SAAT values contain both the unsaturated travel time and the saturated travel time from the watertable to the municipal aquifer (WAAT). The SAAT results also provide insight into the intrinsic vulnerability of the municipal aquifer unit. As such, this approach provides valuable groundwater management and protection information.

The SWAT and SAAT methods were used to rank or categorize the vulnerability within the 25-year time of travel capture zones, and the vulnerability ranking was used to score the vulnerability within the capture zones. The SWAT analysis (and the computation of the component values) provides additional insight into the intrinsic vulnerability within a wellfield. It is understood that the ISI vulnerability method is subject to some uncertainty as it is calculated independently from the groundwater modelling, or other knowledge of the groundwater flow system. Computation of the UZAT, SAAT, WWAT, and SWAT provides insight into travel times from the ground surface to the well, and an enhanced understanding of portions of the projected capture zone that actually contribute to the well.

Of particular importance, the SWAT analysis includes a consideration of the flow system that underlies a projected capture zone and travels toward a well (ISI calculations have no such consideration). The plan-view projection of three-dimensional capture zones onto the ground surface is typically used for groundwater protection purposes. However, the vulnerability of the land surface above a capture zone is only pertinent in areas where the local flow system contributes to the underlying capture zone. Consequently, in some cases, much of the water recharged above a capture zone may be part of a local flow system that flows past a well or to other local discharge zones; this water does not contribute to the well. Such is the case in Inglewood Well 3 and Cheltenham PW1/PW2 which extract water from a deeper groundwater flow system.

In all cases, the time required for a particle to travel from the ground surface to the well is longer than for the previously mapped capture zones which ignore the time of travel through the unsaturated zone. Similarly, the time required for a particle to travel from the watertable to the well is often considerably longer than the capture zone would suggest. This occurs because the backward-tracked particles used to generate the capture zones often remain within the municipal aquifer throughout the capture zone.

Constructed or natural preferential pathways such as improperly abandoned boreholes or breaches in aquitards may be present within the capture zones, and these pathways may allow contaminants to move rapidly from the ground surface to the underlying aquifer. The SWAT calculations do not take these features into account, and therefore are less conservative or precautionary than TOT capture zones produced using a reverse particle tracking approach.

In general, the SWAT assessment has provided knowledge that is consistent with water quality observations. In comparison with the ISI values computed as part of the earlier WHPA study (AquaResource, 2007), the SWAT assessment provided additional insight and refinement. This is largely because the SWAT assessment is more physical and takes more of the geological setting into account. The refinement is particularly important for wellfields where confining beds overlie the capture zone and limit the portion of the ground surface that actually contributes to the well / wellfield; this consideration is pertinent for the following wellfelds (Alton Wells 3/ 4, Inglewood Well 3, and Cheltenham PW1/PW2).

In the case of the Alton Wells 3/ 4, it was found that the SWAT analysis and the observed water quality were inconsistent. The SWAT analysis suggests relatively long travel times along the length of the capture zone, whereas the observed water quality suggests potential local sources of contribution. This discrepancy is largely caused by a paucity of data west of Alton, where there are steep topographic changes, and near the wellfield the contribution to regional flow of the nearby buried bedrock valley is poorly understood. This results in higher than normal uncertainty in the SWAT results at this wellfield.

The ISI-based vulnerability rating completed in the earlier WHPA Study (AquaResource, 2007) was used within the time of travel capture zones to calculate vulnerability scores for general contaminants, DNAPLs and pathogens. In this study, the vulnerability rating was conducted using the SWAT methods, and the scoring was again completed for the three groups of potential contaminants for both the SWAT and WWAT times of travel zones (e.g. SWAT times of 0 to 5 years). In general, the vulnerability of Caledon Village Well 3, and Inglewood Wells 1/2 to surficial contaminants range from moderate to high, while Caledon Village Well 4, Inglewood Well 3 and Cheltenham PW1/PW2 range from low to moderate as those wells are completed in confined aquifers. The SWAT vulnerability calculated for Alton 3/4 was also low, however as this method contradicts water quality measurements, earlier ISI-based methods are encouraged to be carried forward into the Water Quality Risk Assessment.

An uncertainty assessment of the analyses was completed in two ways, including 1) through the simulation of six sensitivity scenarios, and 2) through the analysis of conceptualization, data distribution, travel of time delineation and SWAT/WWAT delineation methods. This assessment highlighted that the SWAT / WWAT vulnerability assessment contained a high level of uncertainty for the majority of the capture zones due to a general a paucity of data and uncertainties in the conceptual model, as well as the uncertainties associated with the municipal aquifer hydraulic conductivity (within half an order of magnitude), as slight adjustments in conductivity can have significant impacts on the resultant vulnerability.

The uncertainty associated with the conceptualization in Alton particularly leads to a high degree of uncertainty with the SWAT vulnerability assessment for this area. As a result, this method is not recommended for application within the Water Quality Risk Assessment.

5 REFERENCES

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Figures

Appendix A
SWAT and UZAT Work Flow

Peel WHPA – SWAT Analysis – Workflow

WWAT (Forwards particle tracking)

Confined model – head on slice 1 is assumed to be watertable elevation
Exported 50m grid of watertable / slice 1 head
Applied 250m buffer around existing 25-year capture zone (from backward PT)
Used (9,077) pixels within these buffers as start location for forward particle tracking with a start elevation of 10cm below the watertable
Ran forward particle tracking (FPT) in FeFlow with default parameters
Start by 3D cursor (from file)
Porosity: 0.30
Final time [d]: 1.00e+33 (steady state)
Runge Kutta accuracy: 1.00e-04
Maximal Runge Kutta steps per element: 200
Minimal time between saved pathline points [d]: 2.156450e-04
Minimal step size factor: 5.00e-12
Maximal element switches: 10
From exported FPT dat file, deleted all track points except start and end location (command line tool: particleTracks.exe)
In Manifold:
Found particles that reach a well based on:

1) 300m buffer around each well of interest
2) particle end elevation relative to screened interval elevation

See “wellsInModel_ofInterest Buffer” drawing for details:
Contains 300m buffer around wells of interest and – based on the screened interval elevations (zMin ScrSL / zMax ScrSL) – “acceptable” particle end elevations (zMin / zMax). Used in combination with Qry_03__asignEndLoc
Flagged found particles as target = “well” (would be better to use the actual well name, to double check if release area (relArea) and target match)
Tracked captured particles back to release location (Qry_04__propagateEndToBeginLoc)
Deleted all end locations and those start locations that were not flagged as target = “well”

→ maps of WWATs (for each scenario)

Qry_06__combineScenarios combines data of all scenarios to one table
Qry_07a_minWWAT finds the minimum WWAT where more than one scenario returned a WWAT for the same release location
Qry_08a_finalWWATs finds the final WWATs → finalWWATs drawing

UZAT (FeFlow IFM)

Developed an IFM to calculate the UZAT:
Input data: locID, x/y location, host element (mapped in Manifold; API in FeFlow buggy)

Additional data from model: *recharge* of host element, K_x for each (partially) unsaturated layer, watertable elevation = head of slice 1, top and bottom slice elevations of each unsaturated layers

$$UZAT = \frac{d_{wt} \cdot \theta_m}{q_z} = \frac{d_{wt}}{q_z} \cdot \frac{\sum [d_i \cdot \theta_{m,i}]}{\sum d_i} = \frac{\sum [d_i \cdot \theta_{m,i}]}{q_z} = \frac{\sum_{ful} [(z_i - z_{i+1}) \cdot \theta_{m,i}] + {}_{pul}[(z_i - h_1) \cdot \theta_{m,i}]}{q_z}$$

$UZAT$	unsaturated zone advection time
d_{wt}	depth to watertable
θ_m	mobile moisture content
q_z	infiltration rate
d_i	(partially) unsaturated layer thickness
z_i	slice elevation
h_1	slice 1 head = watertable elevation
ful	for all fully unsaturated layers
pul	for the partially unsaturated layer

If the unsaturated zone contains several model layers: equivalent θ_m = arithmetic mean of θ_m weighted by layer thickness

Approximation for mobile moisture content:

$$\theta_m = \begin{cases} 0.10 & sand & K > 10^{-5}[m/s] \\ 0.25 & loam & otherwise \\ 0.40 & clay & K < 10^{-7}[m/s] \end{cases}$$

Cases to check:

$$UZAT = \begin{cases} \text{0.0} & \text{water table > ground suface} & \text{h}_{01} > \text{z}_{01} \\ \text{0.0} & \text{recharge = 0.0 (wetland)} & \text{q}_\text{z} = 0.0 \\ \text{error flag} & \text{water table < last model slice} & \text{h}_{01} < \text{z}_{\text{ns}} \\ \text{UZAT} & \text{otherwise} & \end{cases}$$

Qry_05__uzatRelLocs was used to retrieve locations for UZAT calculations
IFM uzat_confModel was used to calculate and export UZATs in FeFlow
UZATs were imported to Manifold and linked to WWATs through relID
UZATs were added on to WWATs (Qry_06__combineScenarios)
Qry_06__combineScenarios also combines data of all scenarios to one table
Qry_07__minSumAT finds the minimum SWAT where more than one scenario returned a SWAT for the same release location
Qry_08__finalSWATs finds the final SWATs → final SWAT drawing