Appendix 13 – Uncertainty Analysis of Vulnerability Assessment

A13-Uncertainty Analysis of Vulnerability Assessment

Based on the Technical Rules, the uncertainty assessment of WHPA is to include:

- an evaluation of the uncertainty associated with the assessment of the vulnerability of groundwater within the area of interest (low, medium, high vulnerability),
- an evaluation of the uncertainty associated with the delineation of the WHPA and
- an assignment of an uncertainty rating (high or low) for each vulnerable area.

The *technical rules* also state that an analysis of the uncertainty, characterized by 'high' or 'low', shall be made with respect to the delineation and assessment of *wellhead protection areas*. The factors to be considered in the analysis include:

- the distribution, variability, quality and relevance of data used;
- the ability of the methods and models used to accurately reflect the flow processes in the hydrological / hydrogeological system;
- the quality assurance and quality control procedures applied;
- the extent and level of calibration of models
- the accuracy of the groundwater vulnerability categories to effectively assess the relative vulnerability of underlying hydrogeological features.

The evaluation of uncertainty is a very subjective process and varied between studies. The key considerations of the evaluation in each study are discussed below by topic area and study. This includes the uncertainty in the delineation of the WHPA, the assessment of the vulnerability in the WHPA and the consideration of transport pathways. For uncertainty in vulnerability scoring for *WHPA-E* associated with *GUDI* wells, the accuracy to which the area vulnerability factor and the source vulnerability factor effectively assesses the relative vulnerability of the hydrological features must also be considered. The uncertainty associated with the delineation of HVA and SGRA are also considered in this appendix and summarized in the appropriate subsection of Section 4.0 of the Assessment Report.

1.1 WHPA Uncertainty

1.1.1. Uncertainty in the Delineation of WHPA-A to D

The uncertainty in the delineation of the Wellhead Protection Areas (WHPA) is evaluated in each study. This is discussed by study in the following sections in many cases by direct quotations from the studies.

1.1.1.1. London, Middlesex Centre & Thames Centre (Birr, Dorchester, London - Fanshawe and Hyde Park back up wells, Melrose and Thorndale) WHPA-A to D

As summarized in Source Protection Study, London, Middlesex Centre & Thames Centre Wellfield Source Protection Study Vulnerability Assessment Report Final Draft Report (October 16, 2009):

> "The delineation of the *wellhead protection areas* comprises a number of assumptions and estimates based on point data such as lithology described in water well records and hydrogeological information provided from technical reports. Each model was developed making the most use of the available data, and therefore the results represent the best estimate that can be made based on that data. Improvements in the models can be made based on any additional information that becomes available in the future. Even with this uncertainty, the wellhead delineation process provides a good indication of the source of the water for the water supply system, which can facilitate a good water resource protection policy.
>
> Overall, significant data gaps are identified if observed. These gaps include information on groundwater recharge values and the heterogeneity in the hydraulic conductivity of the aquifer and aquitard. In addition, better information on the hydraulic levels in the aquifer in the local/regional area would be beneficial, and could be used to improve the

model. Should future pumping rates differ than those used in the model, then a reassessment of the modeled capture zones should be performed.

Groundwater recharge values used in the model greatly control the width of the modelled capture zone. This value is often used to calibrate the model, and is not measured directly. The uncertainty associated with this factor is considered high.

The static water levels recorded in the water well records are notably erratic in nature. Improvement to the model would involve installation of several monitoring wells in key areas and additional hydrogeological studies (including pumping test).

For many of the systems there are no observation wells. When available hydraulic head levels used during model calibration were taken from water levels at different times of the year and over several decades, a more recent and comprehensive survey of hydraulic head levels would provide for a more accurate calibration in all areas. The hydraulic head levels used for calibration, while useful for comparison, could be offset by as much as 2 to 3 m due to seasonal fluctuation or other influences. Nevertheless, it is not expected that the variation would cause significant changes in the interpreted direction of the capture zones. As a result, the uncertainty associated with this factor is considered low.

The heterogeneity of overburden aquifer hydraulic conductivity could only be evaluated at a cursory level. Since hydraulic conductivity and other parameters can vary by as much as two orders of magnitude within the same hydraulic unit, it is likely that significant variation exists within these systems. This heterogeneity could not be completely identified based on the data available for the development of the model. Uncertainty associated with this factor is considered high.

For shallow overburden systems (e.g. Dorchester), the *WHPA* -B, and *WHPA* -C receive a low uncertainty. The rationale for this decision is that the hydrogeology of the overburden aquifer is not complex (shallow relatively homogeneous unconfined aquifer,

with good quality calibration wells). A high uncertainty is given to *WHPA* -D in the overburden aquifer as the uncertainty of the model is higher at large travel times.

The most significant limitations for the confined overburden groundwater flow models are the assumption that the aquifer is continuous over the entire model area. Confined overburden aquifers are known to be discontinuous and coincide with the depositional environment that occurred during interstadial periods in which the aquifers were formed. However, considering the limited extent of the 25-year time of travel area and the correlation of the intermediate aquifer at other wells in an area, the uncertainty associated with this factor is considered low.

For bedrock aquifers the delineation of the *wellhead protection areas* comprise a number of assumptions and estimates based on point data such as lithology described in water well records and hydrogeological information provided from technical reports. The most significant limitations for bedrock groundwater flow model are that there is little information on the geology of the area and few monitoring wells to calibrate the model.

As a result of these factors, there is significant uncertainty associated with the modelled capture zones. Even with this uncertainty, the wellhead delineation process provides a good indication of the source of the water for the water supply system, which can facilitate a good water resource protection policy."

1.1.1.2. Oxford WHPA-A to D

The uncertainty of WHPA delineation is **high** for almost all wellfields of the Oxford systems (Beachville, Embro, Hickson, Ingersoll, Innerkip, Lakeside, Mount Elgin, Tavistock, Thamesford and Woodstock-urban wellfield). The exception is the rural wells of the Woodstock system (Thornton and Tabor overburden wells), which are assigned a **low** uncertainty in delineation. According to the County of Oxford Source Protection Technical Studies Report ‘Groundwater Vulnerability Assessment for the Wellhead Protection Areas in the County of Oxford’ (April 2011), there is uncertainty in the effective porosity used in the capture zone time-of-travel

delineation for the bedrock production wells. The fractured bedrock aquifer flow system was simplified into an equivalent porous media system (a common groundwater modeling approach), resulting in uncertainty in properties of the bedrock, such as hydraulic conductivity. These limitations apply to the systems of Beachville, Embro, Hickson, Ingersoll, Innerkip, Lakeside, Mount Elgin, which are comprised of only bedrock wells, and to the bedrock wells of the Tavistock, Thamesford and Woodstock systems. For the Thamesford overburden wells, uncertainty stems from local variability in hydraulic conductivity values estimated from pump tests in the vicinity of the wells. For the Tavistock overburden well, the capture zone was developed using a low pumping rate, and is relatively long and narrow, leading to a higher uncertainty in the WHPA delineation. There is a lower uncertainty associated with the Woodstock rural overburden supply wells (Thornton, Tabor and the planned well) as they have been studied in detail (outside of the source protection program) and there is considerable data available on the hydrogeology, both locally and regionally.

1.1.1.3. Perth WHPA-A to D

The vulnerability assessment and the WHPA (time of travel) delineation are based on a number of parameters, each of which contributes to the overall uncertainty. For all groundwater systems, there is a high uncertainty associated with hydraulic head levels, groundwater recharge, and the nature of aquifer. Groundwater head levels are taken from the WWIS which are recorded at different times of the year and over several decades. Furthermore, sub-surface properties can only be measured where boreholes exist. The resulting uncertainty is not simply the sum of the uncertainties of all the individual parameters. Some parameters are more influential and have a greater affect on the uncertainty. For example doubling the pump rate influences the shape of WHPA capture zone more than a doubling of conductivity of the aquifer. Fractured bedrock aquifers of Stratford and St. Marys were modeled with higher hydraulic conductivity values. All capture zones in fractured bedrock are therefore considered to have high uncertainty.

Groundwater recharge values are estimated and not measured directly. The nature of the aquifer matrix and its ability to transmit water through the aquifers and the resultant hydraulic

conductivity could not be confidently estimated based on the data available (pump test data). A significant limitation for the groundwater flow models is the assumption that an aquifer is continuous over the entire model area. The geology which controls the aquifer geometry is very rarely laterally continuous or of uniform thickness over broad areas of the landscape. However, the extent of the 25-year time of travel area is limited and, the uncertainty associated with this factor is therefore considered low. Probably, the most significant limitation for a groundwater flow model is the unpredictable/ unknown nature of the regional groundwater flow direction at the site of the municipal well which controls the direction of the WHPA. In general the models have undergone sensitivity analysis and through the various studies, been peer reviewed and at this time, although there is uncertainty, the best available science has been employed and the uncertainty is adequate for source protection purposes.

1.1.2. Uncertainty associated with Vulnerability Assessment (WHPA-A to D)

The groundwater vulnerability assessment was based on the Intrinsic Susceptibility Index (ISI) methodology in Perth and Middlesex. Overall, the uncertainty associated with the groundwater vulnerability map is deemed low, as there appears to be a consistent regional trend in the ISI results. However, uncertainty associated with the vulnerability assessment of the individual system using *ISI* varies between high and low.

From the Perth study, the groundwater vulnerability assessment of Stratford, Shakespeare and St. Pauls WHPA are assigned low uncertainty levels, due to the low vulnerability within the flow model domain. High uncertainty levels are assigned to the groundwater vulnerability assessment of Mitchell (due to the presence of a sand lens), Sebringville (due to the uncertainty in the permeability of the overburden layer), and St. Marys (due to low spatial density of wells and the high spatial variation of the overburden thickness).

From the London-Middlesex study, a low uncertainty is assigned to Fanshawe (City of London back up wellfield), Birr, Thorndale and Dorchester. There is high uncertainty in the groundwater vulnerability assessment of Hyde Park and Melrose due to the presence of few wells in the capture zones.

The groundwater vulnerability within the County of Oxford has been assessed in previous studies using three methodologies (AVI, ISI and SWAT). Excerpts surrounding the discussion from the County of Oxford Source Protection Technical Studies Report 'Groundwater Vulnerability Assessment for the Wellhead Protection Areas in the County of Oxford' (April 2011) are included below. Note that the ISI results from an earlier study (referred to below) were not used; instead the AVI results were used as they were found to provide a more realistic representation of the aquifer examined.

> "The intrinsic groundwater vulnerability within the County of Oxford has been assessed using three methodologies (AVI, ISI, SWAT). The resulting map products were reviewed as part of this groundwater vulnerability assessment, and some minor adjustments were made by a hydrogeologist based on professional judgment. The adjustments included infilling of apparent gaps within the vulnerability mapping of the WHPA, smoothing of contacts, and removal of relatively small anomalies that were not clearly supported by the available hydrogeological information. As with most of the regional scale hydrogeological work in the Province of Ontario, there is a heavy reliance on information from the water well record database maintained by the Ministry of the Environment, and this would typically involve a high level of uncertainty. However, the previous work (Golder 2001, 2003, 2005) included an in-depth review of many of the water well records and the incorporation of other sources of information, such as the surficial (Quaternary) geological mapping, in the vulnerability mapping. In a general sense, the intrinsic vulnerability mapping (SWAT, AVI) procedures used in the groundwater vulnerability assessment have a **low** uncertainty" with the exceptions of Innerkip and Tavistock. At Innerkip, "The AVI mapping appears irregular and difficult to confirm in the vicinity of the WHPA". For Tavistock, "Uncertainty in the bedrock characterization is **high**", and "There are significant gaps and variability in the AVI for the overburden aquifer".

1.2 Uncertainty associated with Transport Pathways (WHPA-A to D)

Some uncertainty is associated with the approach to the mapping of transport pathway information for all well systems. Since information on the presence or absence of *transport pathways* did not involve confirmatory site visits and visual inspection alone would not be

conclusive as to whether a transport pathway exists, the actual presence of the identified *transport pathways* is unknown. Therefore, the mapped extent of the area where these *transport pathways* exist is deemed conservative. Throughout all of the studies, the features of concern would be poorly maintained water wells or oil and gas wells and many of these locations are unknown. Where vulnerability has been adjusted based on an area of increased density of potential transport pathways the location of the individual pathways is less of a concern and therefore the uncertainty associated with adjusting the vulnerability of the area is limited as to whether the potential pathways are poorly constructed or maintained. As this methodology is applied to an area rather than to individual features the number of features which are potentially transport pathways further reduces the uncertainty.

1.3 Overall WHPA-A to D Uncertainty

Based on the discussion above, the uncertainty associated with the vulnerability assessment of the 22 groundwater systems *Wellhead Protection Areas* is to be identified as 'Low' or 'High', as required by the *technical rules*. The overall uncertainty is largely affected by the uncertainty associated with the *wellhead protection area* modelling rather than the aquifer vulnerability assessment for all systems or the adjustments due to transport pathways.

As discussed above, the peer reviewers have had considerable discussion about uncertainty with the consultants who have undertaken the studies for ground water vulnerability assessment. This was also consistent with the uncertainty associated with the Intake Protection Zones in the other Source Protection Areas of the region. Through that discussion it became apparent that there is considerable subjectivity to the assignment of the uncertainty factors. It has been suggested that upon completion of the peer review of all of the reports that an overall assessment and comparison of the uncertainty be undertaken so that relative comparison between studies can be made and priorities for future assessment can be identified. It is important to understand that a high uncertainty associated with any aspects of the work does not suggest that the conclusions are inappropriate for the purposes that the results are being used. This is merely an acknowledgement of the potential for a better understanding with further analysis or data. If it were identified that the uncertainty was too great, additional work

would have been undertaken to reduce the level of uncertainty if data were available to support the additional work. Even with the completion of additional work, it is unlikely that all uncertainty can be eliminated.

1.4 WHPA-E Uncertainty

For the GUDI wells at the Dorchester, Fanshawe and St. Marys wellfields, uncertainty was assigned to the WHPA-E delineation and to the vulnerability scoring as per the Dillon Consulting Ltd. study 'WHPA-E and F Delineation and Vulnerability Assessment –Dorchester, Fanshawe and St. Marys Municipal Water Supplies' (May 2011). For the GUDI wells at the Thamesford and Woodstock (rural) wellfields, uncertainty was assigned to the WHPA-E delineation and to the vulnerability scoring as per the Dillon Consulting Ltd. study 'WHPA-E Delineation and Vulnerability Assessment – Thamesford, Woodstock and Tillsonburg Municipal Water Supplies' (May 2011).

Known and reliable empirical equations were used to determine the 2-year flow estimation and hydraulic calculations for Big Swamp Drain near the Dorchester wells, and for tributaries in the St. Marys and Thamesford study areas. The cross-section characteristics were obtained from the Digital Elevation Model and confirmed during field surveys. The calibrated hydraulic HEC-RAS model used for the WHPA-E instream delineations for St. Marys (extent up the North Thames River) and Thamesford (extent up the Middle Thames River) contained sufficient detail in the vicinity of the well and the study area to provide a high confidence in the delineation. No travel time analysis was needed for the Woodstock (rural) and Fanshawe WHPA-Es. Waterbodies considered in these WHPA-Es (such as creeks and ponds) were buffered with a 120 m zone as prescribed in the Technical Rules. Therefore, the uncertainty level assigned to each of the WHPA-E delineations for Dorchester, Fanshawe, St. Marys, Thamesford and Woodstock (rural) is **low**.

The area vulnerability factors assigned to each of the WHPA-Es delineated is based on known land use data, soil types, permeability, slopes, hydrological and hydraulic conditions of the area.

All these data were available in sufficient detail and have low uncertainty. Therefore, the degree of uncertainty related to each of the area vulnerability factors for Dorchester, Fanshawe, St. Marys, Thamesford and Woodstock (rural) is **low**.

The source vulnerability factor for WHPA-E is based on known well design characteristics (depth of the well, distance to the surface water feature). Sufficient information is available to assign each source vulnerability factor with a high level of confidence. The degree of uncertainty related to the source vulnerability factor for each WHPA-E of the Dorchester, Fanshawe, St. Marys, Thamesford and Woodstock (rural) systems is **low**.

The area and source vulnerability factors are multiplied to obtain the vulnerability score for each WHPA-E delineated. Considering the low uncertainty assigned to these factors, the uncertainty of the vulnerability score assigned to each WHPA-E delineation for Dorchester, Fanshawe, St. Marys, Thamesford and Woodstock (rural) is deemed **low**.

Considering the low uncertainty in both the WHPA-E delineation and vulnerability scoring, the overall uncertainty level assigned to each WHPA-E for Dorchester, Fanshawe, St. Marys, Thamesford and Woodstock (rural) is **low**.

1.5 Highly Vulnerable Aquifers

The *Highly Vulnerable Aquifer* area mapping product is a derivative product based primarily on ISI mapping. The ISI mapping is based on assigning an index based on aquifer, confining materials and water level information identified by drillers as recorded in the Water Well Information System (WWIS). The uncertainty in the *ISI* product is considered high due to a number of factors including:

- Uncertainty associated with the location information and therefore the accuracy of the elevation used in interpreting the description of depth in the *WWIS*
- Uncertainty associated with the material description in the *WWIS*
- Uncertainty associated with water table mapping

- The interpolation process associated with this mapping (and limited data in some areas)

In conclusion, the uncertainty is high in the use of the *WWIS*. The high uncertainty associated with individual data is offset to some degree by the high amount of data included in the *WWIS*. The location and presence of sand and gravel deposits in the Surficial Geology (OGS) mapping are based on a different data set from the *WWIS*. The level of uncertainty is reduced substantially due to the agreement of the two mapping products and the incorporation of professional judgement. The impact of the uncertainty in the low and medium vulnerability areas is minimal from a Source Protection Planning perspective. There is uncertainty related to the Highly Vulnerable Areas (HVA) although the product is acceptable for the purposes of delineating the Highly Vulnerable Areas. This uncertainty is associated with the data sets available for use in this analysis and would exist irrespective of whether the other methods identified in the rules were used to delineate the Highly Vulnerable Areas. Additional work to map the extent and thickness of aquifers in the region would greatly reduce the uncertainty.

1.6 Significant Groundwater Recharge Areas

The uncertainty associated with the delineation of the SGRA is discussed in the Significant Groundwater Recharge Area technical memorandum (UTRCA, May 2010).

> "Groundwater recharge is one of the more elusive quantities to estimate at any level of water budget analysis. Recharge in the present analysis is derived from a continuous GAWSER model for each HRU/Climate zone combination within the UTRSPA. The GAWSER model relies on surficial geology mapping which is presented as a continuous surface, but clearly all areas are not sampled in the creation of the mapping, and some interpolation is used in the creation of these maps. This interpolation carries with it a degree of uncertainty. In any modelling exercise there is an attempt to calibrate the model being used with observed field data with varying degrees of success. In the case of GAWSER modelling, median monthly flows derived from the model are compared with median monthly flows with have been measured, on the long term, at key Environment Canada hydrometric stations. A further discussion of the GAWSER

calibration process is found in the SWS Tier 2 integrated model document (SWS 2010). Published stream flow values at these locations carry with them a certain degree of uncertainty, and this is discussed in detail in the TSR Tier 1 water budget report (TSR, 2010), Section 8.1.1.4.

We should keep in mind that inherent in the stream flow records are the effects of flow augmentation from upstream reservoirs (Wildwood and Pittock), as well as water added from other sources (i.e. Great Lake or groundwater) in the form of pollution control plant effluent. Further more, stream flow records are also affected by discharges from quarry dewatering operations, and also are somewhat reduced by surface water withdrawals, particularly in dry months. These numbers are accounted for in the modelling process as much as is possible, however we need to also realize that these numbers do affect the output and calculation of the recharge rates for the various HRU/climate zone combinations by GAWSER.

As the estimation of SGRAs are based upon the estimate of recharge, this also would have a degree of uncertainty associated with it."

1.7 Summary

The peer reviewers have had considerable discussion with the consultants who have undertaken the studies for both surface water and ground water vulnerability assessment in the Thames-Sydenham and Region. Through that discussion it has become apparent that there is considerable subjectivity to the assignment of the uncertainty factors. It has been suggested that upon completion of the peer review of all of the reports that an overall assessment and comparison of the uncertainty be undertaken so that relative comparison between studies can be made and priorities for future assessment can be identified. It is important to understand that a high uncertainty associated with any aspect of the work does not suggest that the conclusions are inappropriate for the purposes that the results are being used. This is merely an acknowledgement of the potential for a better understanding with further analysis or data. If it

were identified that the uncertainty was too great, additional work would have been undertaken to reduce the level of uncertainty if data were available to support the additional work. Even with the completion of additional work, it is unlikely that all uncertainty can be eliminated. The Source Protection Committee is satisfied that the uncertainty of the vulnerability assessment is low enough for the purposes intended.